UNCLASSIFIED

AD NUMBER

AD084477

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution authorized to DoD and DoD contractors only; Administrative/Operational Use; NOV 1955. Other requests shall be referred to Air Force Cambridge Research Center, Geophysics Research Directorate, Hanscom AFB, MA.

AUTHORITY

per dup doc. 26 sep 1985

THIS PAGE IS UNCLASSIFIED

N

AD-084477

[?]-TR-55-222

GEOPHYSICAL RESEARCH PAPERS

No. 42

PROCEEDINGS ON THE CONFERENCE ON ATMOSPHERIC ELECTRICITY

Edited by

ROBERT E. HOLZER

University of California at Los Angelos

and

WALDO E. SMITH

American Geophysical Union, Washington, D. C.

NOVEMBER 1955

GEOPHYSICS RESEARCH DIRECTORATE

AIR FORCE CAMBRIDGE RESEARCH CENTER

AIR RESEARCH AND DEVELOPMENT COMMAND

(1) W. D. Parkinson, (2) R. H. D. Barklie, (3) Henry A. Miranda, Jr., (4) P. H. Wyckoff, (5) S. C. Coroniti, (6) P. Goldberg, (7) Waldo Smith, (8) P. J. Nolan, (9) H. Israel, (10) J. Fuchs, (11) D. Lee Harris, (12) M. J. aufm Kampe, (13) P. Pluvinage, (14) T. W. Wormell, (15) J. Bricard, (16) L. G. Smith, (17) L. Koenigsfeld, (18) Mrs. O. H. Gish, (19) J. W. Nelson, (20) O. H. Gish, (21) Florence van Straten, (22) J. Alan Chalmers, (23) Seville Chapman, (24) R. E. Holzer, (25) Margery C. Hyland, (26) Maria M. Mahoney, (27) H. Weickmann, (28) S. E. Reynolds, (29) J. H. Hughes, (30) V. Schaefer, (31) Jacob Dinger, (32) E. S. Cotton, (33) Rita C. Sagalyn, (34) W. F. G. Swann, (35) H. G. Byers, (36) J. Kuettner, (37) R. T. Burnight, (38) Elwood Maple, (39) A. R. Hogg, (40) H. Norinder, (41) Arthur E. Bent, (42) H. W. Kasemir, (43) G. Faucher, (44) G. F. Schilling, (45) Y. Tamura, (46) P. M. Crumley, (47) C. Russell Smallman, (48) Harold O. Curtis, (49) Stanley Ruttenberg, (50) Bernard Vonnegut, (51) R. M. Cunningham

AFCRC-TR-55-222

GEOPHYSICAL RESEARCH PAPERS

No. 42

PROCEEDINGS ON THE CONFERENCE ON ATMOSPHERIC ELECTRICITY

Held at
WENTWORTH-BY-THE-SEA, PORTSMOUTH, NEW HAMPSHIRE
MAY 19-21, 1954

Edited by

ROBERT E. HOLZER
University of California at Los Angeles

and

WALDO E. SMITH
American Geophysical Union, Washington, D. C.

NOVEMBER 1955

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH CENTER
BEDFORD, MASSACHUSETTS

TABLE OF CONTENTS

Frontispiece
Preface
Address of Welcome to the Conference .... P. H. Wyckoff 1
The Present Status of Atmospheric Electricity .... W. F. G. Swann 3

Sessions on May 19, 1954 Relating to Atmospheric Electrical Phenomena
Synoptical Researches on Atmospheric Electricity .... H. Israël 11
Study of the Variation of Potential Gradient with Altitude and Correlated Meteorological Conditions .... L. Koenigsfeld 21
Aircraft Investigation of the Large-Ion Content and Conductivity of the Atmosphere .... Rita Callahan Sagalyn and Gerard A. Faucher 27
Conductivity Measurements in the Stratosphere .... C. G. Stergis, S. C. Coroniti, A. Nazarek, D. E. Kotas, D. W. Seymour, and J. V. Werme 43
On the Variation of Electrical Conductivity of Air with Elevation .. Gerhard F. Schilling 53
Atmospheric Electricity Associated with Jet Streams .... Vincent J. Schaefer 59
Diurnal Variations in Atmospheric Radioactivity .... E. S. Cotton 67
Discussion Relating to the Above Papers 78

Sessions on May 20, 1954 Relating to Atmospheric Electrical Phenomena
A Survey of Air-Earth Current Observations .... A. R. Hogg 86
Measurement of the Air-Earth Current Density .... H. W. Kasemir 91
A Program of Simultaneous Measurement of Air-Earth Current Density .. R. E. Holzer 96
Atmospheric Electrical Measurements in the Pacific Ocean
S. Ruttenberg and R. E. Holzer 101
Some Results of Atmospheric Electricity Measurements on the Greenland Icecap
P. Pluvinage 109
The Photo-Electric Counter and Its Application for Measuring Diffusion Coefficients
P. J. Nolan 113
Effects of Wind and Space Charge on Corona Point Discharge, Particularly from Aircraft .... Seville Chapman 120
Report on Some Observations on Atmospheric Electricity .... Josef Fuchs 135
Effects of Radioactive Debris from Nuclear Explosions on the Electrical Conductivity of the Lower Atmosphere .... D. Lee Harris 140
Discussion Relating to the Above Papers 147

Sessions on May 21, 1954 Relating to Thunderstorm and Disturbed Weather
Theories of Thunderstorm Electrification--Some General Considerations
T. W. Wormell 157
Thunderstorm Charge Structure and Suggested Electrification Mechanisms
S. E. Reynolds 162
Possible Mechanism for the Formation of Thunderstorm Electricity .. Bernard Vonnegut 169
Some Remarks Concerning the Effectiveness of the Lightning Rod and the Distribution of Lightning Currents in the Earth .... J. Bricard 182
An Analysis of Electric Field after Lightning Discharges .... Yuichi Tamura 190
Magnetic-Field Variations in the Vicinity of Lightning .... Harald Norinder 201
Experimental Study of Electrification of Snow ... Harald Norinder and Reinhards Siksna 208
Point Discharge .... J. Alan Chalmers 222
The Electric Charge of Raindrops .... L. G. Smith 227
The Systematic Electrification of Precipitation by Ionic Diffusion .... Ross Gunn 232
Discussion Relating to the Above Papers 237

Appendix 1--Alphabetical List of the Participants in the Conference 245

PREFACE

The field of atmospheric electricity is one of the oldest branches of meteorological physics. In its long history, it has yielded a number of interesting results, including those which revealed the existence of cosmic rays. In general, progress in the field has been slow and at times discouraging because of the very great complexity of the atmospheric processes which control the electrical phenomena observed. However, within the last few years there has been a revival of interest in atmospheric electricity. The increased activity has been stimulated, in part, by improvement in methods of measurements and the opportunities to obtain data in the free atmosphere remote from the surface of the Earth, in part, by the necessity of solving practical problems attendent upon increased use of aircraft and rockets, and, in part, by the growing recognition that electrical measurements may be sensitive indicators of meteorological phenomena.

Members of the staff and consultants of the Geophysical Research Directorate of the Air Force Cambridge Research Center and the Office of Naval Research felt that the time was ripe for a conference on atmospheric electrical problems under the auspices of the American Geophysical Union. The prime objectives of the Conference were to appraise the current status of the science of atmospheric electricity and the arts and techniques related thereto, and to consider possible pathways to fruitful future research. Incidental to this, the Conference aimed to bring together key workers in the field from throughout the world in order that they might have the benefit of personal acquaintance and in order that the science might benefit from cross-fertilization of ideas that association might provide. To this end, arrangements for the meeting were made at a location which would encourage informal discussions and which would be somewhat removed from diversionary activities.

These objectives were fully attained through the three-day conference at Wentworth-by-the-Sea, Portsmouth, New Hampshire in May, 1954. The feeling was expressed by some that by virtue of this endeavor the science had gained two years or more in time.

A secondary objective of the conference, perhaps, more accurately, a by-product, is the publication of the conference proceedings including research papers, reports and discussions. The research papers present a number of the most recent developments in the field. The reports review past developments stating or restating the author's views of the present status of the field and the outlook for the future. The discussions were spontaneous, and as given here were prepared from a verbatim transcript, sharply edited, though retaining their verbatim flavor. It is realized that since the Conference was held, several of the papers have appeared in established scientific journals in a form similar to, if not identical to, the form of their presentation to the Conference. In order that all the papers may be assembled under one cover they are again presented here. Because the present volume is a record of conference proceedings, the editors have accepted all papers presented. In a few instances, errors have been pointed out to the authors but in no case has a manuscript been refused if the author has not agreed to make suggested corrections.

The history of the conference goes back several years to plans laid by the late George R. Wait and by Samuel Coroniti of the Air Force Cambridge Research Center. Dr. Wait did not live to see his dream materialize. However, his colleague Mr. Coroniti served the Conference as Project Scientist for the Air Force, and was intimately associated with all phases of the work relating to the Conference.

The Editors

PROCEEDINGS OF THE CONFERENCE ON ATMOSPHERIC ELECTRICITY, MAY 19-21, 1954

ADDRESS OF WELCOME TO THE CONFERENCE

P. H. WYCKOFF

Geophysical Research Directorate, Air Force Cambridge Research Center
Cambridge, Massachusetts

On behalf of the Air Research and Development Command of the United States Air Force and the Office of Naval Research of the United States Navy, I would like to welcome you to this Conference. Many of you have traveled from distant corners of the Earth to be with us today, and we are very appreciative that you have considered it worth while to do so.

You may wonder why this Conference on Atmospheric Electricity was sponsored by two branches of the Armed Forces of the United States. It would appear at first thought that such a subject would be far removed from the problems of the military services. During the last war, however, the military services learned that science and modern warfare must go hand in hand. The Blitzkrieg of yesterday has been replaced by the Witzkrieg of today. It is only natural, therefore, that the military man must look to the scientist as a colleague for a solution of their mutual problems. One of the fundamental fields where the military must rely upon the scientist is in the scientific evaluation of the environment in which aircraft are flown and battles are fought. In this country we cover the entire field of the atmosphere and the surface of the Earth by the term 'geophysics.' One important part of geophysics is certainly atmospheric electricity, and we feel that it is necessary to understand the role of atmospheric electricity in the Earth's atmosphere in order to understand the military problem of environment. Precipitation static is as much a problem of flight as turbulence and down drafts. Thunderstorms are as much a problem of safety as fog and icing. As we will undoubtedly discuss at this Conference, we have found that atmospheric electricity has contributed heavily to the general field of meteorology by furnishing the meteorologist with a sensitive tool for defining mixing layers and as a tracer for air masses. Those of us who are working with the military feel that the contributions made by atmospheric electricity have hardly scratched the surface. We realize that there is much yet to be done and much more to be understood. We have asked you here today because we recognize that this group represents the outstanding competency in the world today in atmospheric electricity. We feel that the future of the science of atmospheric electricity rests within your hands, and that we can rely upon you to guide us into those aspects of atmospheric electricity which will be the most fruitful from the scientific point of view.

Again, may I express our appreciation for your kindness in accepting our invitation, and we hope that you will find these three days interesting and profitable to you and that you will enjoy yourselves during your brief stay with us.

THE PRESENT STATUS OF ATMOSPHERIC ELECTRICITY

W. F. G. Swann

Director, Bartol Research Foundation of the Franklin Institute
Swarthmore, Pennsylvania
Dinner Address, May 20, 1955

The subject of atmospheric electricity has, in the past, concerned itself primarily with three sections: (1) The nature and origin of the atmospheric conductivity; (2) the nature and origin of the potential gradient, and the equivalent topic, the origin and maintenance of the Earth's negative charge; (3) the origin and nature of precipitation phenomena, thunderstorms, etc. Finally, it used to be customary to include a fourth section under the title 'The Penetrating Radiation.' However, this last subject has outgrown all of its relations in the last three decades, and has taken unto itself another and more dignified title, so that, under this title, 'The Cosmic Radiation,' it stands by itself, concerned only with its own affairs and the cosmic phenomena of the universe. It lives in a state of affluence supported by much money, and consorts only with the aristocrats of physics - the nuclear physicists. We poor atmospheric electric physicists can hardly claim it any more as a relative. We must be content with one another and our old friends, the meteorologists, whose popular representative is the weather man, for after all, the princes of cosmic rays give very little to our science. It is true that out of their abundance they seem to support the conductivity over the ocean, but to the conductivity on land they only make a token payment. It must be confessed, however, that we, the atmospheric electric physicists, give the cosmic ray people very little from our own science.

I have been advised to keep this speech on the non-technical level, and the natural limitations of time prevent my doing more than touching upon certain topics. Apart from a few remarks on measurements in general, I must direct attention to the situation as regards atmospheric conductivity and must make my main concern the origin and maintenance of the Earth's charge.

To refer briefly to a matter having to do with measurements, one is conscious, particularly in the early history of the subject, of many things masquerading as fundamental phenomena but which, as a matter of fact, are, in the last analysis, merely the natural consequences of the operation of the laws of electrostatics. Thus, for example, neglecting the motion of electricity produced by air currents, we may say that the fact that the conductivity increases with altitude automatically results in the existence of a potential gradient which diminishes with altitude and this in turn, by the fundamental laws of electrostatics, results in the existence in the atmosphere, below the point at which the potential gradient is small, of a positive charge equal and opposite to the charge upon the surface of the Earth. The increase of conductivity with altitude is itself a primary phenomenon depending upon such factors as the distribution of radioactive material in the atmosphere, the variation of mobility of ions with pressure, and so forth. However, with this variation of conductivity established, the atmospheric charge distribution and the potential gradient variation follow as an inevitable consequence, and if we started with a condition in which there were no potential variation and no positive charge, the flow of electricity itself would result in the appearance of a positive charge and of a variation of potential gradient with altitude.

Even today, a word of caution is necessary to the effect that, in appraising the relative significance of atmospheric electric phenomena, it is important that we should separate things which are more or less independent from those which are directly related by the known laws of electricity and magnetism. Intimately related to this matter is that of the significance of instrumental measurements. Frequently the relation of that which is measured to the fundamental quantity which it was the intention to measure is not free from uncertainty.

Thus, for example, a hemispherical mound a mile in diameter and half a mile high might seem, superficially, to present a reasonably flat surface at the top, for potential gradient measurements. However, since the field on the top of such a hemisphere, regardless of its dimensions, is three times the field over a flat surface obtained when the hemisphere is removed, it is easily seen that serious errors may result from neglect of the inevitable implications of the fundamental electrostatic laws which govern this matter. Lack of sufficient care in a correct appraisal of the effects of the atmospheric potential gradient in inducing charge on parts of the measuring apparatus has, in the past, led to serious errors in the results obtained, errors which have sometimes masqueraded as fundamental phenomena of nature calling apparently for erudite discussions as to their causes.

Atmospheric electricity is not the only science in which this kind of thing has happened. The study of electrets has revealed phenomena which seem at first sight puzzling, and indeed, have been considered by some to be inconsistent with the laws of electrostatics, only to find that all is explained in a simple manner when the implications of these laws are traced.

Another matter which has hindered the interpretation of atmospehric electric data has been the sensitivity of such data to local phenomena of such a nature that, through their complexity, it is difficult to define the extent of their influence. Dust, smoke, sand, etc., have often been responsible for yielding results which are of very little value as regards their interpretable significance.

Fortunately, the great oceans have provided us with a territory more uniform in their characteristics and freer from undefinable local agencies than is the case with land territories; and so it has come to pass that ocean observations have tended to give us a clearer picture of the essentials. Also, to some extent, observations at high altitudes, in spite of their difficulty, are susceptible of cleaner interpretation than are those at the ordinary ground observatory.

<u>Atmospheric Conductivity</u>--Atmospheric conductivity results from a balance between rate of production of ions by ionizing sources and rate of dissipation of ions by recombination with one another or with dust or other nuclei. With a wide degree of generality, we may assume that the time rate of change of the number n of ions per cc of one sign is related to the rate of production q per cc by the equation

$$dn/dt = q - \alpha n^2 - \beta n$$

The βn term is frequently neglected in ordinary laboratory phenomena having to do with artificially produced ionization, but in atmospheric electricity it plays a fundamental role. It is natural to attribute this term to the presence of dust nuclei and the like. The matter is not as simple as might at first appear, however, for even after such nuclei have been removed as far as it seems feasible to remove them, there yet seems a limit beyond which β cannot be further reduced. Many years ago, I played with the idea that the βn term might arise from columnar ionization along the tracks of the ionizing particle, and indeed this idea has been developed by others since that time. However, I was never able to convince myself of the harmonization of columnar ionization with the phenomena observed in the case where the ionizing particles are electrons. I believe that the significance of the βn term calls for more study even at the present time.

The extent to which different ionizing agencies contribute to the conductivity has always been a subject of primary interest. According to Prof. Victor F. Hess, Table 1 represents the contribution to q, the number of ions produced per cc per second, by the various agencies referred to overland.

Table 2, due to Hess, is interesting as indicating the variation of the rate of production of ions by the various agencies, with distance from the ground over the relatively small range of one meter. Naturally, such data may be expected to be highly local in character.

Table 1--Production of ions near the Earth's surface over land in ion-pairs/cm^2 sec

Ionizer	Ionizing rays			Total
	α	β	γ	
Radioactive matter				
In the Earth	0	0.1	3.0	3.1
In the air	4.6	0.2	0.15	4.9
Cosmic radiation	...	...	...	1.5
Total				9.5

Table 2--Production of ion pairs near the Earth's surface

Distance from the surface	Ion pairs			
	α rays	β rays	γ rays	cosmic rays
cm				
3	3.58	2.18	3.76	1.96
100	1.76	0.47	3.21	1.96

Over the great oceans, ionization is primarily limited to the cosmic-ray contribution, so that the rate of production of ions over land is six times as great as the corresponding value over the sea. The fact that the number of ions per cc over the ocean is fully half as great as over land calls for a smaller value of β for the ocean than for the land. However, the relative magnitude of β necessary to harmonize the land and sea ionization is one which seems reasonable in the light of the possibilities.

Atmospheric contamination by atomic explosions--In view of the relatively small ion content of the atmosphere, and of the large amount of radioactive material released in an atomic explosion, it is interesting to inquire the extent to which such an explosion can materially affect atmospheric electric observations.

The whole of the atmosphere over the Earth contains normally about 6×10^7 curies of radium emanation and this is responsible for most of the ionization. Now, an explosion of a bomb of the Hiroshima type puts into the atmosphere an amount of radioactive material which, measured in curies, is about three times this amount 24 hours after the explosion. One week after the explosion it is about one-fifth of this amount. A year after the explosion it is about 1/600th of this amount.

Now, of course, all of this radioactive material does not distribute itself uniformly immediately. It probably goes along in very concentrated form following the direction of the air currents. There seems to be a considerable amount of misunderstanding about this matter. I think, however, that anyone who has watched the dissipation of smoke from an airplane writing in the sky would have no difficulty in believing that if one released 100 captive balloons at an altitude of a few thousand feet, he would not find them wandering off in all directions hither and yon, but would observe that they traveled along more or less together in such fashion that even after a journey of many miles one might expect to find them more or less clustered together or, at any rate, not very widely separated. It is to be anticipated that the radioactive material will travel along in very much the same fashion, so that whether or not it will constitute a hazard, will depend upon where one happens to be in relation to the wind currents and, of course, upon precipitation; for of there is no precipitation, the rays from the radioactive material will be absorbed to a large extent before reaching the Earth.

Most of the radioactive products from fission bombs have a short life and are not likely to contaminate the atmosphere for very long. However, in the case of the hydrogen bomb we are concerned with trittium, which has a half life of 10,000 years. What becomes fixed, however, in building a hydrogen bomb of assigned energy yield is a certain minimum number of trittium atoms. If the process is, let us say, ten per cent efficient, then ten per cent of these atoms will be pumped into the atmosphere. However, the very fact that the half life is so long - 10,000 years - means that the fraction of the total number of atoms which break up per second, and so the contaminatory effect on our experiments is not necessarily large. In addition to this, the range of penetration of the radiation from trittium is very small. The effect lasts a long time, but physicists do not usually do experiments which last 10,000 years; only astronomers do that, and they do it in contemplation.

Of course, contamination over the sea tends to be rapidly disposed of by the products of contamination becoming spread throughout the volume of the ocean waters, so that their radiations can not get through to the surface. Radioactive material deposited on land can be a more serious matter. Presumably, however, much of it would get into the air and in process of time this would disappear aloft or become dissolved in the oceans.

The origin and maintenance of the Earth's charge--I now turn to the all-important question of the Earth's charge and its maintenance. The average value of the potential gradient at sea level is of the order 120 V/m. The potential gradient varies considerably over land, but over the great oceans it is sensibly constant, and its average surface value is about 126 V/m.

The conductivity of the atmosphere increases with altitude by a factor of 10 for an altitude change of 7000 meters, and in this Conference we have learned of data continuing the increase up to much higher altitudes. The altitude increase of conductivity leads, through direct application of the equation of continuity and the laws of electrostatics, to the conclusion that there should be a positive charge in the atmosphere and that the potential gradient should decrease with altitude. Both of these facts are confirmed by experiment, and the potential gradient at an altitude of ten kilometers is only about two per cent of the sea-level value.

The average value of the surface current density is about 3×10^{-16} amp/cm^2. The total negative conduction current from the whole Earth is about 1800 amperes. The rate of conduction of electricity into and through the atmosphere is sufficient to insure that 90 pct of the Earth's charge would disappear in about ten minutes if there were no means of replenishing the loss.

Theories of the maintenance of the Earth's charge have divided themselves into two main categories: (1) those in which the whole mechanism of replenishment is to be found within the atmosphere itself, or within the Earth, and (2) those in which it is supposed that negatively charged particles are shot from outside though our atmosphere to the Earth.

A third type of theory has envisaged more drastic hypotheses according to which, by a very slight modification of the fundamental laws of electrodynamics, a continual very slow rate of death of positive electricity is maintained as a result of the Earth's rotation, a death amounting to one proton per cc per day. This would result in building up a continually increasing surplus of negative electricity were it not for the conduction current which carries it off into space.

Prominent among the first named category of theories are those involving precipitation, in which it is supposed that through the agency of rain or other forms of precipitation, or through associated lightning flashes, negative charge is brought down to the Earth against the influence of the electric field, builds up thereon, and finally flows back into and through the atmosphere in the form of the atmospheric electric conduction current.

A somewhat different form of mechanism, proposed by Ebert, invoked the fact that ionized air, emerging from the pores of the Earth's surface during periods of falling barometric pressure, comes into the atmosphere with a net positive charge on account of the diffusion of the negative ions to the walls of the pores. The positive ions were supposed to be carried upwards by rising air currents.

The net negative charge on the Earth's surface then built up a field which resulted in the usual negative conduction current which passed into the air, eventually to join with and annul the positive current arising as aforesaid.

Precipitation theories were the first to claim attention. Such theories experienced obstacles prominent among which was the fact that precipitation brought down charges of both signs and, while the negative precipitation was ten times as large as was necessary to maintain the Earth's charge, there was an almost equal precipitation of positive charge, and the evidence of earlier days seemed to indicate that the excess was in favor of the positive sign, that is, of the wrong sign for purposes of maintaining the Earth's charge.

Another obstacle arose from the fact that precipitation theories resulting, as they do, in a separation of charges, with one sign remaining temporarily in the atmosphere while the other sign is deposited on the Earth, lead to a condition in which the opposite charges remain bound to each other's vicinities. The negative density on the Earth is held bound to the positive in the atmosphere, and no surface charge or potential gradient is therefore to be expected outside of the region where precipitation occurs. This difficulty, which also affected the Ebert theory, became alleviated when the effect of the high conductivity of the upper atmosphere became recognized. We have now, in fact, to recognize, to a first approximation, two spherical conductors, the Earth's surface, E, and the so-called conducting layer, S. The displacement of charges in the atmosphere, or from atmosphere to ground, sets up a difference of potential between these layers, a difference of potential which is handed around to all parts of the Earth.

Thus, some of the earlier difficulties confronting precipitation theories evaporated in the light of fuller considerations born of the existence of the conducting layer; however, during the period in which it seemed that these difficulties might be significant, it became customary to seek for more drastic means of replenishment in the form of a compensating current shot into the Earth from outer space. At the time when such a proposal was made by G. C. Simpson, one shuddered at the thought of the particle energies necessary to provide penetration through the atmosphere. However, the development of our knowledge of cosmic rays soon taught us that this matter represented the least of all obstacles to the acceptance of corpuscular replenishment. We are accustomed now to deal in cosmic ray particles with energies hundreds or thousands of times the value necessary for penetration of the atmosphere. However, by the same token, our greater knowledge of these particles has placed greater limitations upon the use which we may permit ourselves to make of them. We now know the actual number of such particles entering the Earth. It is a hundred thousand times too small to present any possibility of using the cosmic rays as a source of replenishment of the Earth's charge, and we have very little reason to believe that we have missed a whole category of charged particles. The only possibility in this direction lies in the supposition that particles of sufficiently high energy would be undetectable; and while there is some theoretical reason to believe that this may be so, the necessity for invoking such a drastic hypothesis has passed. Superposed upon all this is the fact that if we had a corpuscular current sufficient in amount to replenish the loss of the Earth's charge, the rate of production of ions which it would be expected to produce in the atmosphere would be a hundred thousand times that known to exist. I will not deny that it might be possible to doctor up the corpuscular hypothesis to meet the primary objections confronting it. However, in the light of the clarification of the whole picture as represented by precipitation theories, the development of such theories to the point of eliminating the old difficulties which faced them, and the fact that they permit an understanding of diurnal variation phenomena in a manner which, as we shall see, would present a very great problem for any theory based on an incoming corpuscular current, renders it undesirable to pursue the corpuscular hypothesis further in this epoch.

Similar remarks of obsoleteness apply to theories concerned with modification of electrodynamic laws to permit a death of positive electricity as a result of the Earth's rotation, with the accompanying build up of the negative counterpart to supply material for the atmospheric electric conduction current.

Having, therefore, discussed briefly the past history of the subject, let us take a fresh breath and inquire how things stand today. In speculating upon the possibilities, two things emerge as of outstanding significance.

The first matter of importance is the existence of a conducting layer, S, which, with the Earth's surface, E, constitute two spheres, each sphere being at a potential which is the same at all parts but which, in the case of the conducting layer, may vary with time. It is not without interest to observe that if we were to draw these two spheres on a piece of paper, it would be difficult to draw a line so thin that its thickness was not too great to represent the distance between them.

The second matter of outstanding significance is S. J. Mauchly's discovery to the effect that the diurnal variation of the potential gradient follows universal rather than local time over the oceans. This means that apart from local effects, the maximum of the potential gradient always occurs at the same instant at all places on the Earth's surface. It is not without interest to inquire as to the longitude for which this instant is local noon. It so happens that the longitude in question is the longitude of some place in California.

The dependence of the potential gradient upon universal time is something which it is almost impossible to account for on the basis of an incoming corpuscular current of constant intensity coming from some place external to the Earth. Such an incoming corpuscular current of constant magnitude could only be consistent with a diurnal variation by the existence of a distortion of the conducting layer, and a distortion which followed universal time. Thus, for example, if the conducting layer were depressed downwards at some place, the potential gradient would become increased, since the layer is at the same potential at all places. Such phenomena as atmospheric tides would lead only to potential gradient variations which followed local time. The only kind of what I may call pseudo-tide phenomena which could give a potential gradient following universal time in the light of the existence of a constant total supply current is one where the radius of the conducting layer increased periodically with time and equally at all places, and such a motion is not consistent with any known cause. Even if it existed, there is no known cause which could determine its phase. Some years ago, I made a suggestion to the effect that when the Sun was overhead at any place, the layer would be depressed at that place, resulting in an increase of potential gradient. Here again, however, we have a phenomenon which would follow local time.

A possibility intimately related to this idea and based upon a constant total current is the following. Suppose the electrical resistance per unit area between the conducting layer and the Earth varies with time, and to different extents in different places. Then, since the potential of the conducting layer is the same at all places at any instant, the conduction current density will vary from place to place in inverse proportion to the resistance per unit area. If the resistance variations referred to are confined to the higher altitudes, the potential gradient at sea level will vary proportionally to the current density and so inversely proportional to the columnar resistance per unit area. Again, in the normal course of events, we anticipate a variation of columnar resistance, and so of potential gradient, which follows local time. However, by a rather far-fetched hypothesis, we can secure conditions in which a component of the variation follows universal time. Thus, suppose the alteration in columnar resistance follows local time in a general way but that the extent of the variation depends upon local conditions. To take an exaggerated case, suppose that, at a certain longitude, the resistance variation was much greater than anywhere else, possibly on account of local meteorological conditions; then, superposed upon the general local-time variations, we should have a variation following universal time.

It must be admitted that such avenues of escape from the difficulty such as I have here envisaged are very speculative. When, however, we give up the concept of a constant corpuscular current and seek replenishment from the atmosphere itself, matters assume a much more natural role. The basic motivating cause which we now seek is one where the supply current varies with time, and so determines a conduction current and a potential gradient varying with time.

Thus, to take an exaggerated case, suppose we have replenishment as a result of thunderstorms occuring at one place on the Earth's surface and that the thunderstorm frequency at that place follows

cal time. Then the supply current will follow what is local time for that place, and so universal time for the Earth as a whole.

In the next simplest approach to a picture, we may imagine a condition in which thunderstorm activity could be divided into two components, a component which was distributed uniformly over the Earth's surface, and a component of larger value contributed by the specialized region. The first of these components would be expected to result in a potential gradient which showed no diurnal variation, while the second would result in a diurnal variation following universal time. As regards the second, we should have a maximum of potential gradient all over the Earth at the instant when, in the specialized region, there was a maximum of thunderstorm activity. If, 12 hours later, there were a minimum of thunderstorm activity at the specialized place, then at that time we should have a minimum of potential gradient all over the Earth.

If there are two places where the thunderstorm activity has pronounced maxima and minima 12 hours apart, then we shall still get a net potential gradient variation which follows universal time. Of course, if all places are equally favored as regards thunderstorms, the potential gradient will show no time variation at all.

We could secure a 12-hour period by supposing conditions in which, at the specialized place, there was a 12-hour period in thunderstorm activity. However, the fact that the 12-hour period seems to be absent over the oceans, and at the top of the Eiffel Tower, for example, where we are well removed from the complicated meteorological conditions associated with the Earth's surface, these facts invite the supposition that no more complicated assumption than that of the 24-hour period in the thunderstorm activity is necessary to account for the facts.

Now, that the basic ideas underlying the foregoing considerations are in line with the facts is borne out by the fact that the total thunderstorm activity does follow roughly a 24-hour period in universal time, and by the further fact that the time of maximum thunderstorm activity corresponds to the time of maximum potential gradient.

I have already referred to the fact that maximum potential gradient occurs at a time when it is noon in California. I do not wish to attach too much significance to this matter. However, it is evident that an important field of activity is to be found in the correlation of thunderstorm activity with atmospheric electric data, with special attention to the frequency of occurrence of thunderstorms at different parts of the Earth's surface, and to the seasonal and similar variations of thunderstorm activity in different places.

The situation presented by a thunderstorm is, I believe, typically one roughly represented by an electric doublet in the atmosphere, the positive charge being on the top and the negative charge below. For complete electrostatic considerations we have to envisage the images of this doublet in the Earth below and in the conducting layer above. The net result is that we have negative electricity streaming down to the Earth below and positive electricity streaming up to the conducting layer, where it spreads out, as does the negative charge on the Earth, to the extent necessary to insure constancy of potential for each sphere. The potential difference thus established between the two spheres then sets up the atmospheric-electric conduction current.

A lightning discharge at any place on the Earth's surface might well be detectable at any other part of the surface. Thus, a discharge of 30 coulombs would change the potential difference between the Earth and the conducting layer by δV, where

$$\delta V = [30 \times 3 \times 10^9 (4\pi h)/4\pi r^2] \times 300 \text{ volts}$$

where h is the height of the conducting layer, and r is the Earth's radius. Putting $h \sim 50 \times 10^5$; $r = 6.5 \times 10^8$,

$$\delta V \sim 30 \times 3 \times 10^9 \times 50 \times 10^5 \times 300/4 \times 10^{17}$$

$$\sim (1/3) \times 10^3 \text{ volts.}$$

Even if this were distributed sensibly equally throughout ten kilometers, it would amount to 0.0003 V/cm. Such a voltage should be detectable by radio methods, but in view of the large number of thunderstorms occurring per second, the problem of disentangling the separate storms presents very serious difficulties.

The thought that atmospheric electric phenomena find their origin in the atmosphere itself naturally invites an attempt to balance the various sources of contribution and see whether they add up to zero. Data to this effect have been obtained by Dr. Wormel, who finds, for supply of positive electricity to the Earth, the contributions shown in Table 3 from four sources, (1) the ordinary atmospheric electric current, (2) precipitation, (3) point discharge below clouds, and (4) lightning.

Table 3--Contributions to the supply of positive electricity to the Earth

Source	Contribution
	coulombs/km^2 year
Conduction current	60
Precipitation	20
Point discharge	-100
Lightning	-20

These do not add up to zero but to -40 Coulombs/km^2 yr. However, the average data for the oceans seem to reveal a conduction current nearly twice that assumed by Wormel, and I believe that the consensus of opinion is that the large point discharge current is not really representative of the Earth as a whole, including the oceans. We are fortunate in having Dr. Wormel with us, and doubtless it will be possible to iron this matter out.

Conscious of the fact that the thunderstorm contribution to the Earth must be the negative of the thunderstorm contribution to the conducting layer (since the total contribution must be zero) and recognizing that it is easier to make measurements over a thunder cloud than beneath it, Drs. Gish and Wait, by measuring the conductivity and potential gradient over thunder clouds, have sought to ascertain whether, indeed, the total current from all thunderstorms can provide a balance to the conduction current. They have, in fact, asked themselves the question of how many thunderstorms must be going on at any one time all over the Earth in order to supply to the conducting layer a current equal and opposite to the atmospheric electric current.

As a result of measurements on some 21 storms, they arrive at a figure between 0.5 amp and 0.8 amp as a typical thunderstorm current. Taking 1800 amp as the total conduction current, the number of thunderstorms per second necessary to compensate the conduction current turns out to be 2200 if we take the larger current (0.8 amp) and 3600 if we take the smaller value (0.5 amp). These values for the number of storms are greater than those sometimes quoted, values of the order 1800. However, a consideration of all circumstances makes it not unreasonable to contemplate a value as high as 3600. At any rate, these considerations serve to illustrate the necessity of securing more data in this very important field.

SYNOPTICAL RESEARCHES ON ATMOSPHERIC ELECTRICITY

H. Israël

Meteorologisches Observatorium
Deutscher Wetterdienst
Aachen, Germany

Abstract--Our views on atmospheric-electric phenomena and their causes have undergone considerable changes in recent years. This is particularly true with regard to the clarification of meteorological influences on atmospheric electricity. Every weather phenomenon involves meteorological processes which have electrical effects. Partly these processes act as 'generators' producing atmospheric-electric conditions; partly their activity as 'variable circuit elements' influences the electrical state of the atmosphere. This close relation between meteorology and atmospheric electricity, correctly recognized today, suggests the widening of work in the field of atmospheric electricity towards synoptic research. Two meteorological-electrical steering processes exist: the 'thunderstorm regulation' of world-wide scope, and the more local 'weather regulation.' Correspondingly one may distinguish between a 'large scale air-electric synopsis' and a 'small scale' one. By way of a few examples, our present experience with air-electrical synopsis as well as its capabilities are discussed. Some thoughts are brought up for discussion concerning the further development of the synoptic approach in atmospheric electricity.

Introduction--The problem of the extension of atmospheric electrical work in the direction of synoptical measurements has become increasingly important in recent years. This is part of a broader problem: the search for the roots of atmospheric electrical phenomena.

Fifteen years ago I was present at a meeting where the question was argued 'Does the study of atmospheric electricity belong to meteorology?' This difficulty in classification originates in the fact that the atmospheric-electrical phenomena have both local and global characteristics, that means, one finds simultaneous local and global regulating effects [ISRAËL, 1950].

Investigations during the last few decades have removed this classification difficulty and have led to the now well-known conclusion that the roots of the atmospheric electrical manifestations lie entirely in the field of meteorology. Both of the regulating mechanisms, those that vary from place to place and those that are the same over the whole globe, are of meteorological nature. These mechanisms differ only quantitatively in their operation and therefore in their radius of influence [ISRAËL, 1952ab]. This association between atmospheric electricity and meteorology, today generally accepted, opens the door to new methods and ideas in the work on these phenomena.

Working in the field of geophysics is, as you know, quite different from that in the experimental physics. If we expect relations between physical quantities, we cannot make experiments, but we must look for correlations. This involves methods of statistics. The original discovery of the cause of the global daily variation in the electric field is a good example of the use of this method. The next step is to discover methods to eliminate random results. It is suggested that this can be done by comparing the results of simultaneous measurements at several stations, that is, by means of the synoptical method. The classical example of this is the study of meteorology itself, where the terminology originated and where climatological and synoptical studies have for many years occupied coordinated positions.

In the field of atmospheric electricity, up to the present time, it has been possible to use only the statistical-climatological methods, because a development or expansion in the synoptical direction is possible only after a clarification of the basic correlations between the two branches of the

meteorology and the atmospheric electricity. With this clarification and the removal of some further problems of measuring methods which prevented such a development hitherto, it is possible today, yes, necessary, to place the atmospheric-electric climatology side by side with an atmospheric-electric synopsis. I would like to discuss in the following the possibilities of the synoptical method and to present some practical experiences in this field. At the conclusion I would like to present for discussion several ideas and suggestions for the practical development of this method.

Atmospheric-electric synopsis

General conceptions--The influence of the weather on atmospheric-electric phenomena may be divided in two groups: We can distinguish between the generators, which create the electric field, and the variable circuit elements which influence the behavior of this electric field. In a thunderstorm, a cloud from which rain is falling, in general all motion of charges due to non-electrical forces belong in the generator group. On the other hand, smoke trails, smog in large cities, air-mass variations, or any condition having to do with variation in the aerosol content of the air, are considered as variable circuit elements in the atmospheric-electric circuit. This is generally spoken without regard to the electric space charges, which may be seen as a kind of transition between these two groups. When the space-charges are moved by non-electric forces, for example by wind or eddy diffusion, we have a generator.

Experience has shown that we must distinguish between two atmospheric generator groups: those that have global effects, and those whose radius of activity is limited to a small region [ISRAËL, 1953]. For example, thunderstorms have a global influence on the atmospheric-electric field, where as a mist or non-stormy cloud generally influences the field only locally. In the second group, the variable circuit elements, the consideration as a rule can be limited to the immediate vicinity of the disturbance. The effects of eddy diffusion on aerosols for example will in general be limited to this region of diffusion [ISRAËL, 1951].

If we speak now about synoptical study of atmospheric electricity, we have to remember the two possibilities of influences we mentioned before: According to this the objectives of the two branches of the synoptical study of atmospheric-electricity are different. The first is concerned with global influences and seeks to determine the thunderstorm activity in various parts of the world and to determine the variation in thunderstorm activity from day to day. The other is limited to a smaller region and seeks in detail the correlation between local weather developments and the atmospheric-electrical conditions. In other words, we can differentiate between large-scale and small-scale atmospheric-electrical synopsis. The former requires a network of stations of continental or global magnitude, whereas the latter requires a station-network of much smaller magnitude, that means, one would seldom cover more than 3000 or 4000 sq mi or 10,000 sq km in the latter case.

It is well known that important conclusions about the inner correlations between two geophysical branches can be drawn when daily variations of the elements in question are compared. For this reason, one should also pay attention to the variations of atmospheric-electrical elements in a 24-hour period in synoptical atmospheric-electrical studies. (It is certainly not just a coincidence that the synoptical study of atmospheric electricity began with a comparison of daily variations.)

In determining the localization of stations required, one must remember that the daily variation of the exchange layer is an important factor influencing the atmospheric electricity. Therefore, depending upon our objectives, we must seek out or eliminate regions affected by such exchange. In a global large-scale synoptical study it is necessary to avoid such exchange influences by placing the stations either on the ocean or on a high mountain. For the small-scale meteorological-atmospheric-electrical synopsis, the stations would be suitably placed inland where the lower atmospheric layers can best be studied [ISRAËL, 1954].

These reflections lead to an old point of controversy, namely whether or not we have 'undisturbed days' in atmospheric electricity and, if so, how they should be chosen. As has been shown

previously, there is no satisfactory answer to this question because the question is stated incorrectly [ISRAËL, 1948]. The generally recognized important close association to meteorology forbids the striving toward an abstraction of its effects. More often the problem at hand will determine the conditions under which the study should be made. I shall give three examples of this: For studies not immediately concerned with generator effects, as such, one should try to avoid conditions or regions of generator action, that means, conditions of precipitation and thunderstorms. Second, if the exchange influences are to be studied, then we must try to eliminate the global effects. Third, if the global thunderstorm activity is the objective of investigation, local effects should be avoided.

Now we have to consider another important problem. Speaking of a synopsis, we must be clear that synoptical work involves expansion as well as extension. We must expand by having a network of stations and we have to extend by measuring more than one element. An electric circuit cannot be considered if one measures only the potential difference, the current, or the resistance alone. Similarly, we cannot be satisfied if we record the potential gradient, the air-earth current, or the conductivity alone. We must measure at least two of the elements as many American investigators have done for decades.

By recording one element only we cannot separate influences originating from local and from global effects. I give one example: a variation of the potential gradient may come from a nearby chimney or from a variation of the thunderstorm activity in Southern America. To get an analysis we must without any doubt know at least two elements.

The application of radio-sondes in determining the atmospheric-electrical elements in the free atmosphere is another tool in atmospheric-electrical synopsis. The apparatus for ground as well as for radio-sonde measurements has already been developed [KASEMIR, 1951; KOENIGSFELD and PIRAUX, 1951; and others].

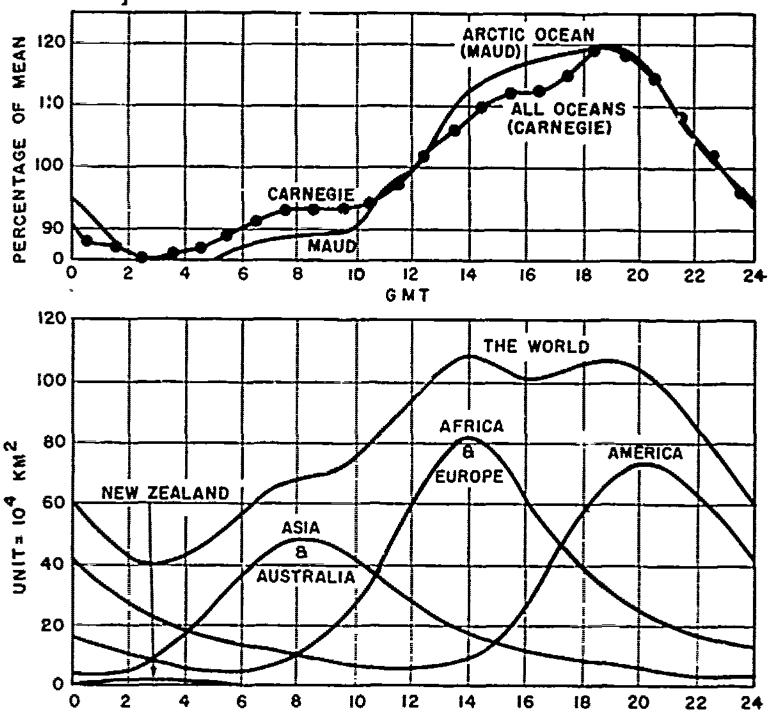


Fig. 1--The daily variation of the potential gradient (a) over the oceans (Maud data for the northern winter only), and (b) over land thunderstorm areas (a place was considered to be in a thunderstorm area if thunder was audible within 60 minutes before or 60 minutes after a specified time) [WHIPPLE and SCRASE, 1936]

Examples for synoptical work--As a first example I have chosen the results of a previous investigation by the Carnegie Institution. Even though the results were developed from a climatological-statistical basis, they lead directly to a synoptical approach. Figure 1 shows the atmospheric-electrical potential gradient and thunderstorm activity as a function of the GMT period and shows the association between the peaks of the potential gradient curve and the peaks of the thunderstorm activity over several continents.

In Figure 2 the daily curves of the potential gradient over the ocean show a systematic seasonal variation. From Figure 2 we notice that the maximum between 6h and 10h at midyear is more pronounced. Since this maximum occurs at the same time as the maximum thunderstorm activity over Asia and Australia, this difference evidently points to a corresponding variation of the number of thunderstorms in this area, which will depend upon whether the dry or wet season prevails. It is only a very small step from this result to large-scale synopsis.

As a further example, (also based upon the work of the Carnegie Institution), we will consider the parallel investigations conducted at Watheroo (West Australia) and on the ocean, which were undertaken to determine the 'columnar resistance' and its daily variation [WAIT, 1942].

Figures 3 and 4 show an example of large-scale synoptical studies on mountaintops. Figure 3 shows the daily variation of the potential gradient, air-earth current, and conductivity at two stations, about 400 km or 250 miles apart, atop the mountains Jungfraujoch (3470 m) and Sonnblick (3100 m) in the Alps, for some days of simultaneous readings in the fall of 1950. Figure 4 shows two days of these recordings. In both figures one can see the close agreement between the two curves. Since these readings were taken at a height which is not affected by the variation in daily exchange, these curves indicate that large-scale influences are apparent. It follows that we can expect the investigations on mountaintops of sufficient height to be as useful for the study of global effects in the atmospheric electricity as investigations on the oceans.

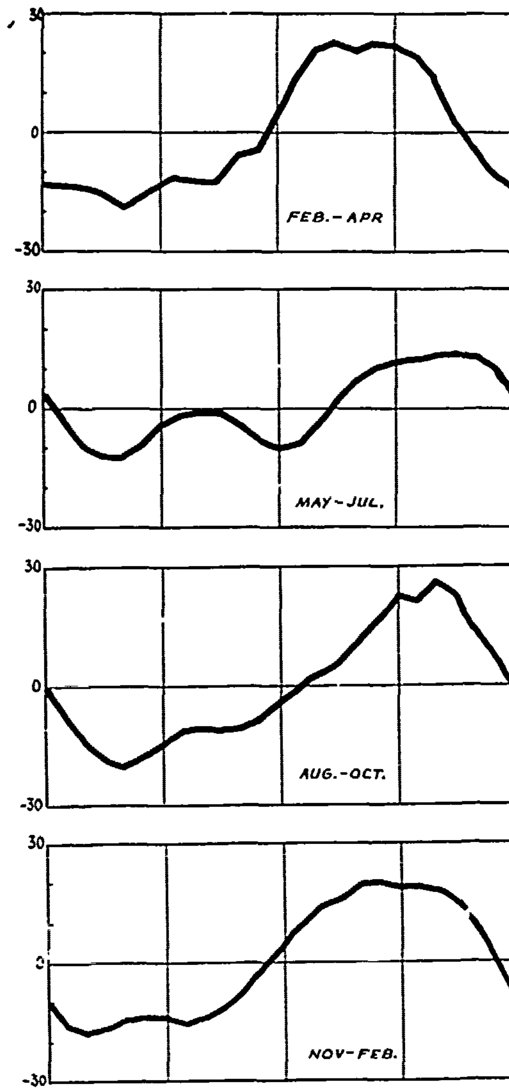


Fig. 2--The daily variation of the potential gradient over the oceans during the four seasons [PARKINSON and TORRESON, 1931]

Figure 5 indicates an example of a small-scale atmospheric-electrical synopsis. One sees the variation of the atmospheric-electrical potential gradient at three stations lying on a straight line about 130 km or 80 miles long (Buchau - Tübingen - Stuttgart) [ISRAËL, 1952b]. One can clearly see that the nature of the daily variations at all three stations is identical: A double-periodic curve was indicated at all three stations on July 3, and a single-periodic curve on July 5. The small amount of information gathered during these seven days does not allow us to draw any detailed

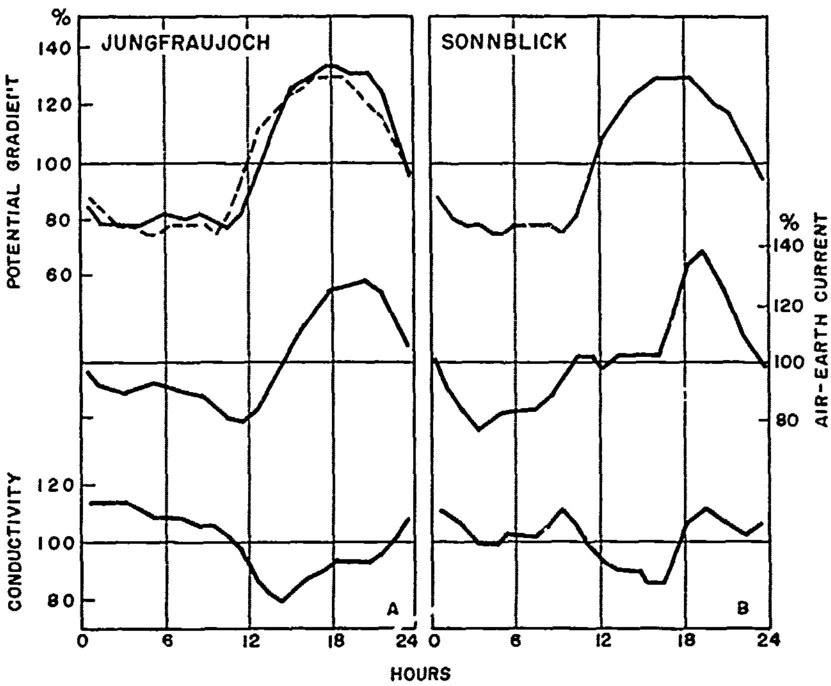


Fig. 3--The diurnal variation of the potential gradient, the air-earth current, and the conductivity at Jungfraujoch (3470 m) and Sonnblick (3100 m) in the Alps for simultaneous readings during some days in 1950

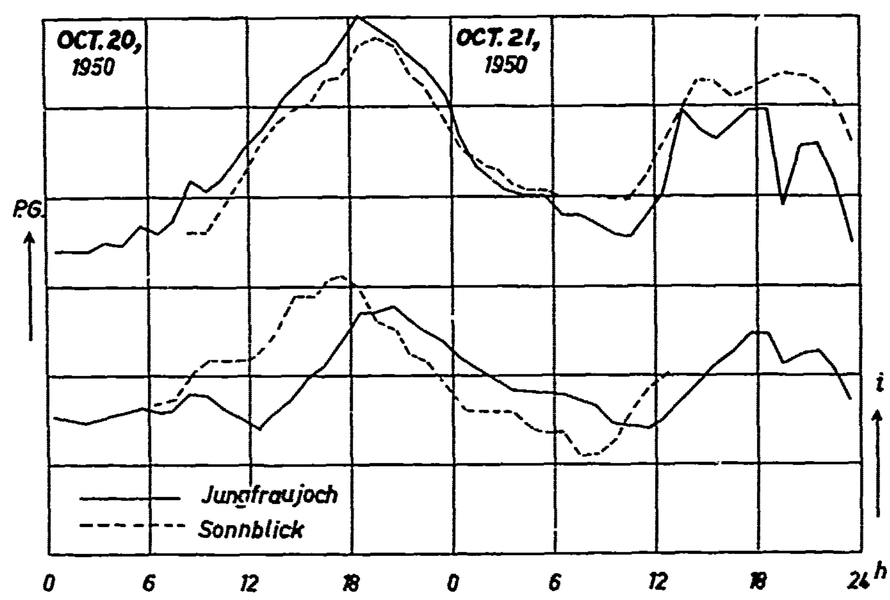


Fig. 4--Simultaneous readings on potential gradient and air-earth current at Jungfraujoch and Sonnblick, October 20-21, 1950

conclusions, but it is evident that we are dealing with meteorological effects of large and small amplitude resulting from eddy diffusion. It is interesting to note that the type of variations is similar in the rural station at Buchau and the city stations at Tübingen and Stuttgart. This shows that in such studies, we can use stations in or near cities with some caution.

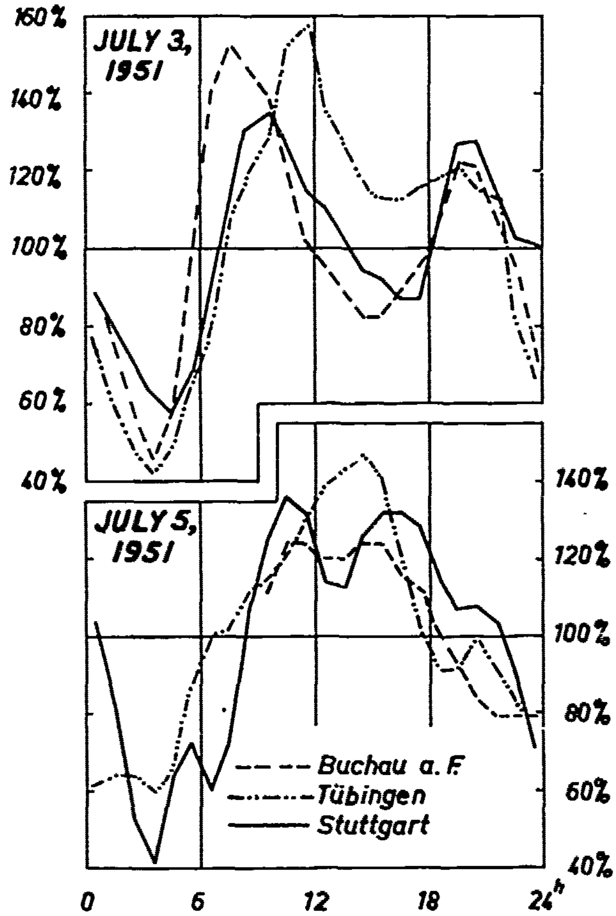


Fig. 5--The daily variation of the potential gradient in southern Germany at Buchau a.F., Tübingen, and Stuttgart; simultaneous readings, July 3 and 5, 1951

To complete this example, Figures 6 to 8 show the potential gradient, air-earth current, and conductivity over a longer period of time at Buchau. The variations from day to day can be seen. I do not wish to go into more detail until further study with simultaneous readings from another station 20 miles away has been completed. I show these figures because the variations from one day to the next indicate the possibilities which are contained in the synoptical atmospheric-electric method of approach.

Conclusion--I have hoped to show the nature and some of the first results of the synoptical method in atmospheric-electrical studies with these examples. These examples must suffice since further investigations of this nature are yet to be conducted. However, such studies are already under way in the United States of America, and with the assistance of the Air Force Research and Development Command I will conduct similar studies in the Alps.

I would like to draw some conclusions from the above examples and present them for discussion. The extension of atmospheric-electrical studies in the synoptical direction requires the continuous

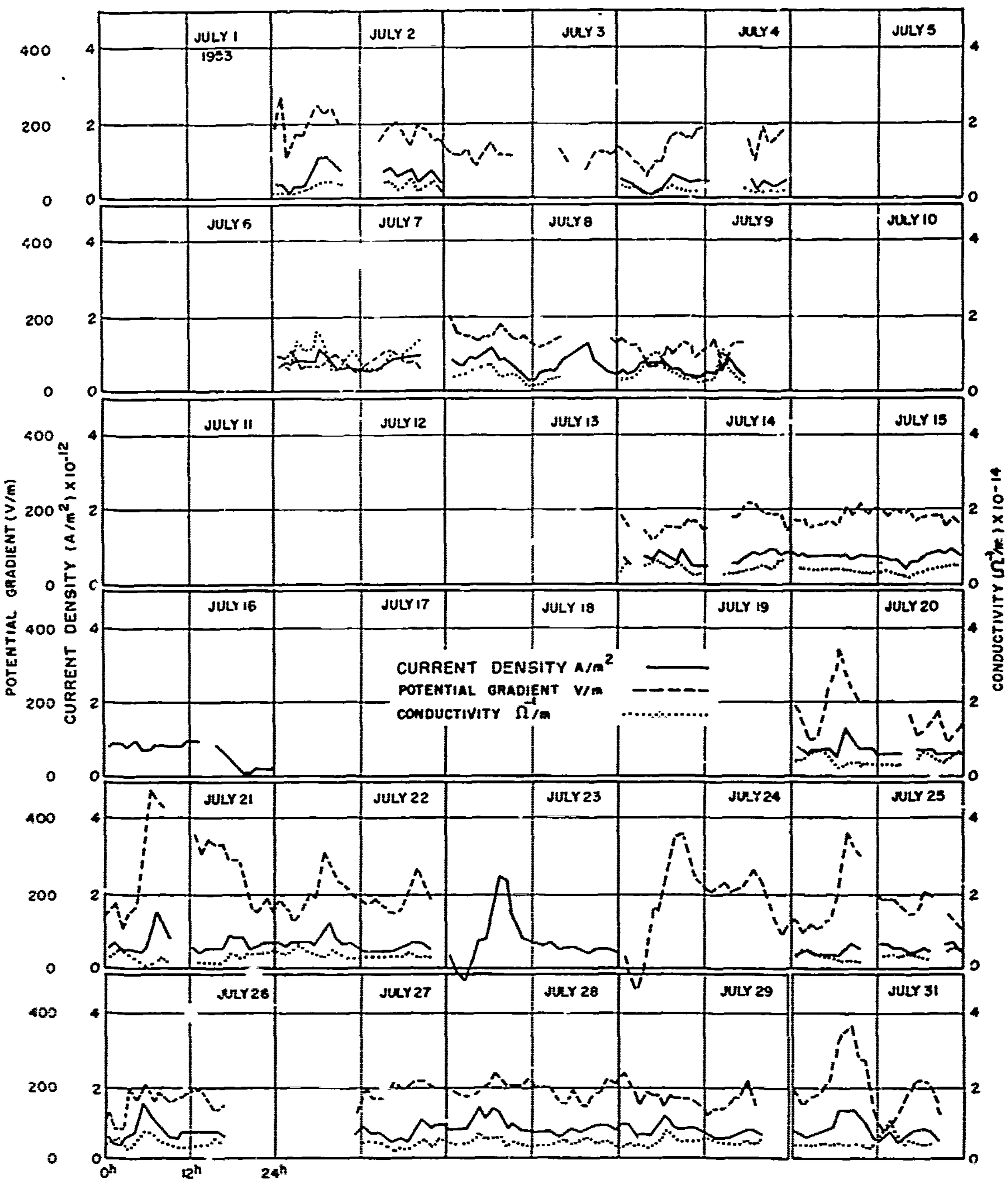


Fig. 6--The variation of the potential gradient, air-earth current, and the conductivity at Buchau a.F., July, 1953

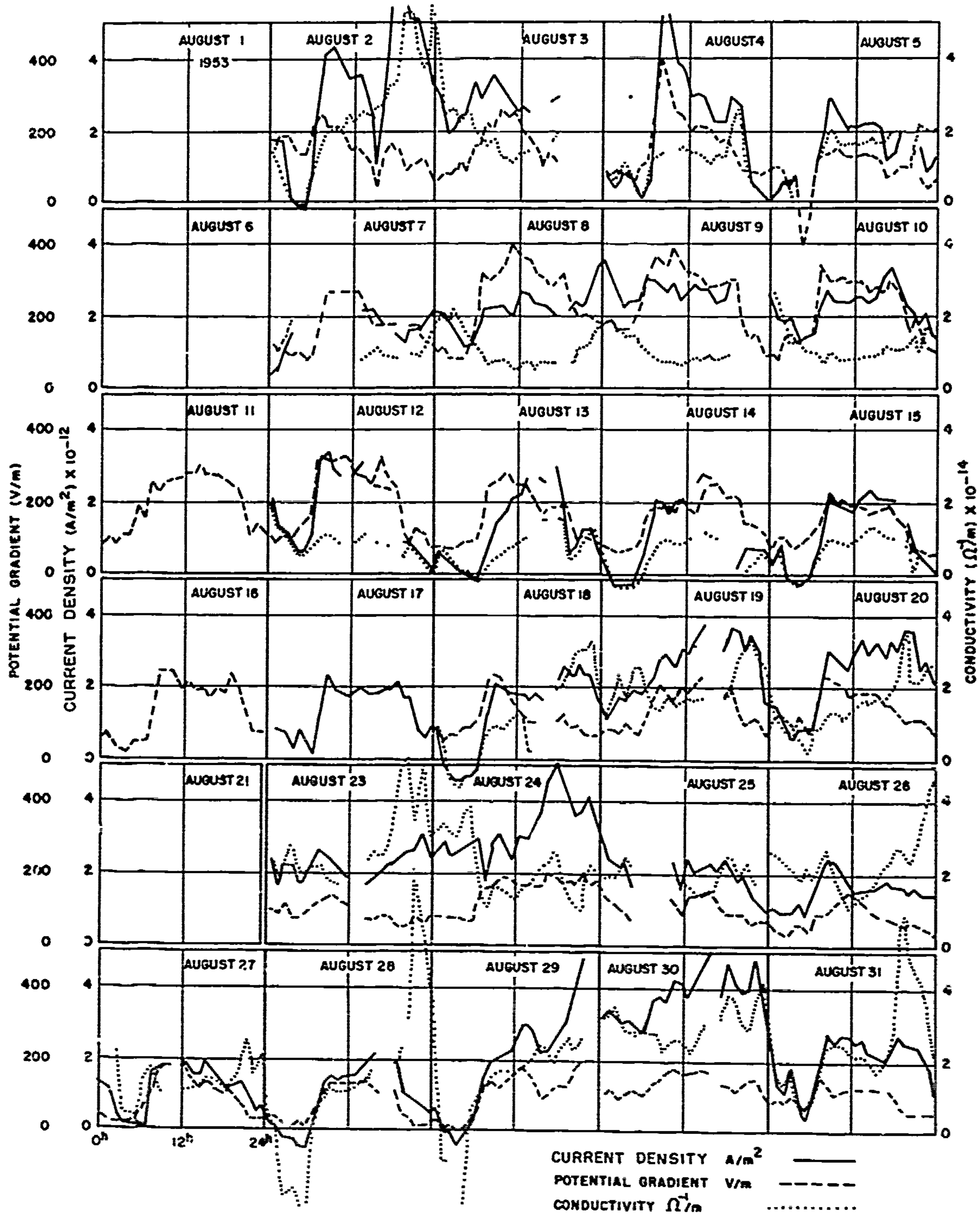


Fig. 7--The variation of the potential gradient, air-earth current, and the conductivity at Buchau a.F., August, 1953

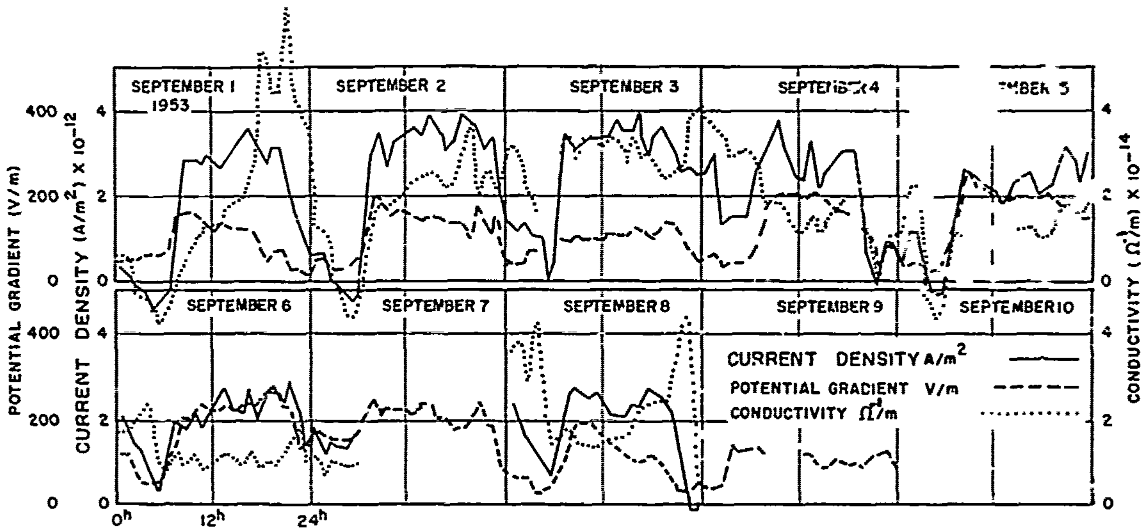


Fig. 8--The variation of the potential gradient, air-earth current, and the conductivity at Buchau a.F., September 1-10, 1953

cooperation of the participating stations. For small-scale atmospheric electrical synopsis this extension can be accomplished by organizing meteorological observation in the respective countries. For large-scale atmospheric electrical synopsis the situation is somewhat more difficult. Teamwork on an international basis is required.

I would like to suggest that we strive toward a closer cooperation between the atmospheric-electric stations over the globe. I believe that we should discuss how such coordination could best be undertaken. I would be very happy if the above procedures open the way for new methods and applications of atmospheric electrical studies. And in conclusion I would like to point out that the coming International Geophysical Year will present particularly favorable conditions for the extension of atmospheric-electrical studies by the synoptical method.

References

ISRAËL, H., Zur Entwicklung der luftelektrischen Grundanschauungen, Archiv Met. Geophys. und Bioklim. (A), v. 2, pp. 367-375, 1950.

ISRAËL, H., The diurnal variation of atmospheric electricity as a meteorologico-aerological phenomenon, J. Met., v. 2, pp. 328-332, 1952a.

ISRAËL, H., Luftelektrizität und Meteorologie, Bericht Deut. Wetterd. in der US-Zone, v. 5, no. 35, pp. 217-223, 1952b.

ISRAËL, H., The atmospheric electric field and its meteorological causes, in Thunderstorm electricity, (H. R. Byers, ed.) pp. 4-23, Univ. Chicago Press, 1953.

ISRAËL, H., Ergebnisse der luftelektrischen Arbeiten in Buchau a.F., Archiv Met., Geophys. und Bioklim., v. 7, pp. 266-282, 1954.

ISRAËL, H., H. W. KASEMIR, and K. WIENERT, Die luftelektrischen Verhältnisse am Jungfraujoch (3470 m), pt. 1, Luftelektrische Tagesgänge und Luftzirkulation, Archiv Met., Geophys. und Bioklim., (A), v. 3, pp. 357-381, 1951.

ISRAËL, H., H. W. KASEMIR, and K. WIENERT, Luftelektrische Tagesgänge und Massenaustausch im Hochgebirge der Alpen (Die luftelektrischen Verhältnisse am Jungfraujoch (3470 m), pt. 2, Vergleichsmessungen am Jungfraujoch und Sonnblick, Archiv Met., Geophys. Bioklim., (A), in press.

ISRAËL, H., and G. LAHMEYER, Studien über das atmosphärische Potentialgefälle, pt. 1, Das Auswahlprinzip der luftelektrisch ungestörten Tage, Terr. Mag., v. 53, pp. 373-386, 1948.

KASEMIR, H. W., An apparatus for simultaneous registration of potential gradient and air-earth current, J. Atmos. Terr. Phys., v. 2, pp. 32-37, 1951.

KOENIGSFELD, L., and PH. PIRAUX, Un nouvel électromètre portatif pour la mesure des charges électrostatiques par système électronique; Son application à la mesure du potentiel atmospherique et à la radiosonde, Inst. R. Met. Belg., Mem., v. 45, 1951.

PARKINSON, W. C., and O. W. TORRESON, The diurnal variation of the electric-potential of the atmosphere over the oceans, Bul. 8, Internat. Assn. Terr. Mag. and Elect., IUGG, C.-R. Stockholm Assembly, pp. 340-345, Paris, 1931.

WAIT, G. R., Electrical resistance of a vertical column of air over Watheroo (Western Australia) and over Huancayo (Peru), Terr. Mag., v. 47, pp. 243-249, 1942.

WHIPPLE, F. J. W., and F. J. SCRASE, Point discharge in the electric field of the Earth, Geophys. Mem.. London, v. 7, no. 68, 1936.

STUDY OF THE VARIATION OF POTENTIAL GRADIENT WITH ALTITUDE AND CORRELATED METEOROLOGICAL CONDITIONS

L. Koenigsfeld

Institut Royal Meteorologique de Belgique
Uccle, Belgium

Abstract--The variation of potential gradient with altitude has been observed during 28 soundings at Uccle between December, 1953, and April, 1954. The patterns of potential gradient are found to correspond to meteorological conditions during the soundings. In particular, the type of air mass has an important influence on the potential gradient. The possible future use of atmospheric electrical measurements in meteorology is discussed briefly.

Introduction--There have been very few measurements of the potential gradient as a function of altitude until the present, and these measurements have been made intermittently and without coordination. We have had the opportunity to make such measurements with regularity by means of a simple method which has been described previously [KOENIGSFELD, 1951]. It has been our purpose to carry out the measurements in different air masses both by day and by night and to study the variations in the potential gradients as a function of meteorological conditions.

All of the results have been obtained with modified English radiosondes of type MK II. The four elements used permitted the measurement of temperature, pressure, humidity, and potential gradient. The modification of the sonde for use with four elements consisted simply in changing the contactor adapted to the weather vane. The fourth element designed for measurement of the potential gradient employs a triode. The filament-grid current of the tube changes the self-inductance of an iron-core coil which modulates the frequency of the transmitted signal [KOENIGSFELD, 1951, 1953]. The filament grid current is controlled by the difference of potential between two radioactive collectors (potential equalizers) with approximately one meter vertical separation, and connected respectively to the filament and plate of the triode.

Calibration--In order to calibration the instrument we have proceeded in two different ways. The first procedure consists in applying a potential difference between the potential equalizers and measuring the corresponding signal frequency. We thus obtain a curve of frequency as a function of the applied potential difference. The second procedure consists in suspending the radiosonde by a nylon cord under a horizontal grid about ten square meters in area and about two meters above the ground. An artificial electric field is established with the grid positive and the ground negative. The variation in the frequency of the transmitted signal is observed as the field is changed. The two methods used gave the same result. We were thus able to show that the radiosonde measured the field created between grid and ground.

Mounting the instrument for flight--Below the balloon (2000 or 750 gr) we suspended a parachute attached by means of a 100-meter cord containing several polystyrene insulators. A 100-meter cord was chosen for two reasons: (1) to have the radiosonde outside the influence of the electric charge on the balloon, and (2) to have the radiosonde far enough away from the balloon so that the apparatus would not swing too much due to the rapid ascent of the balloon in a turbulent atmosphere.

On several occasions we have measured the electrical field below the balloon and have found no distortion of the field. The balloon must be within 20 meters of the sounding apparatus in order

to observe a distortion of the field due to the charge of the balloon, which sometimes has a rather large charge after inflation. We are thus confident of the reliability of our measurements.

Results of the soundings--During the period from December 16, 1953 to April 26, 1954, 28 soundings were made. Nineteen soundings were made during the day at 14h 00m and nine at night at 02h 00m. We have consistently attempted to find different air masses with distinguishing characteristics. Accordingly, ten soundings have been launched during the passage of fronts and five others during stable anticyclonic conditions.

In order to limit the number of graphs, we shall confine ourselves to an examination of three soundings (Fig. 1, 2, and 3) which appear to be the most characteristic and which confirm nearly all of our conclusions.

Explanation of the graphs--On each figure the potential gradient (increasing from right to left) in volts per meter, the temperature, and the relative humidity in per cent are given as abscissas. The altitude in meters and the pressure in millibars are given as ordinates. The temperature is given as a function of pressure. In the dashed curve we have traced the rise of the balloon as a function of time. The potential gradient is plotted as a function of altitude. The moist and dry adiabats are also shown. At the bottom of the plate, the record of the potential one meter above the ground is recorded throughout the day of the ascensions to indicate the state of electrical activity at the surface. A scale of 100 or 200 volts is given. Finally, in order to indicate the general atmospheric situation we have reproduced the meteorological map for the hour nearest the time of the sounding (13h for the sounding at 14h and 0h for the sounding at 2h).

In the case of the sounding of April 26, 1954 (see Fig. 1), we are dealing with a continental air mass, the sky is calm and we have the best condition for a normal distribution of the electric field in the atmosphere.

The electric field at the ground is normal, that is, of the order of 100 V/m. It is seen that in altitude the electric field increases progressively up to the level of maximum humidity and decreases rapidly with weak fluctuations. It is noteworthy that even in a calm atmosphere, there is a sharp increase in the potential gradient around -30° to -33°C; the same phenomena has been found in the case of most of the other soundings. A slight increase in the potential is also evident in traversing the stratosphere; after this the potential gradient varies rather little over a range from zero to ten volts per meter.

In the case of the sounding of February 24, 1954, at 14h (Fig. 2), launched at the time of the passage of a cold front, the atmosphere was more disturbed than in any of the other cases recorded. The potential gradient at the ground is very high, reaching +400 volts at certain times but decreasing rapidly and even reaching -150 volts before the passage of the front. We see again that the potential increases rapidly with altitude reaching 350 v/m in the lowest fracto-stratus and cumulus clouds; the potential gradient does not return to its normal value, but remains very high and variable. We note a sharp increase in the potential gradient, about 45v/m at -32°. Even beyond the stratosphere we have very abnormal variations of the gradient.

A sounding was made about 12 hours after the preceeding, at 02h, February 25, 1954 (Fig. 3). At the ground the potential gradient is weak or negative. It was -10 volts/meter at the time of launching. The gradient increased abruptly with altitude, reaching 450 v/m as in the preceeding sounding. There is a sharp decrease near 1000 m followed by an increase to 300 v/m at about 1300 m. Up to this level the sounding resembled the preceeding sounding. However, above this level the gradient decreased rapidly becoming normal or even weak as in all night soundings. We note that the great jump at -32° is still visible but only four volts/meter.

It would seem that equilibrium is re-established during the night and that gradient becomes much more stable and weaker above 2000 m. Moreover, this is the main difference between day and night soundings.

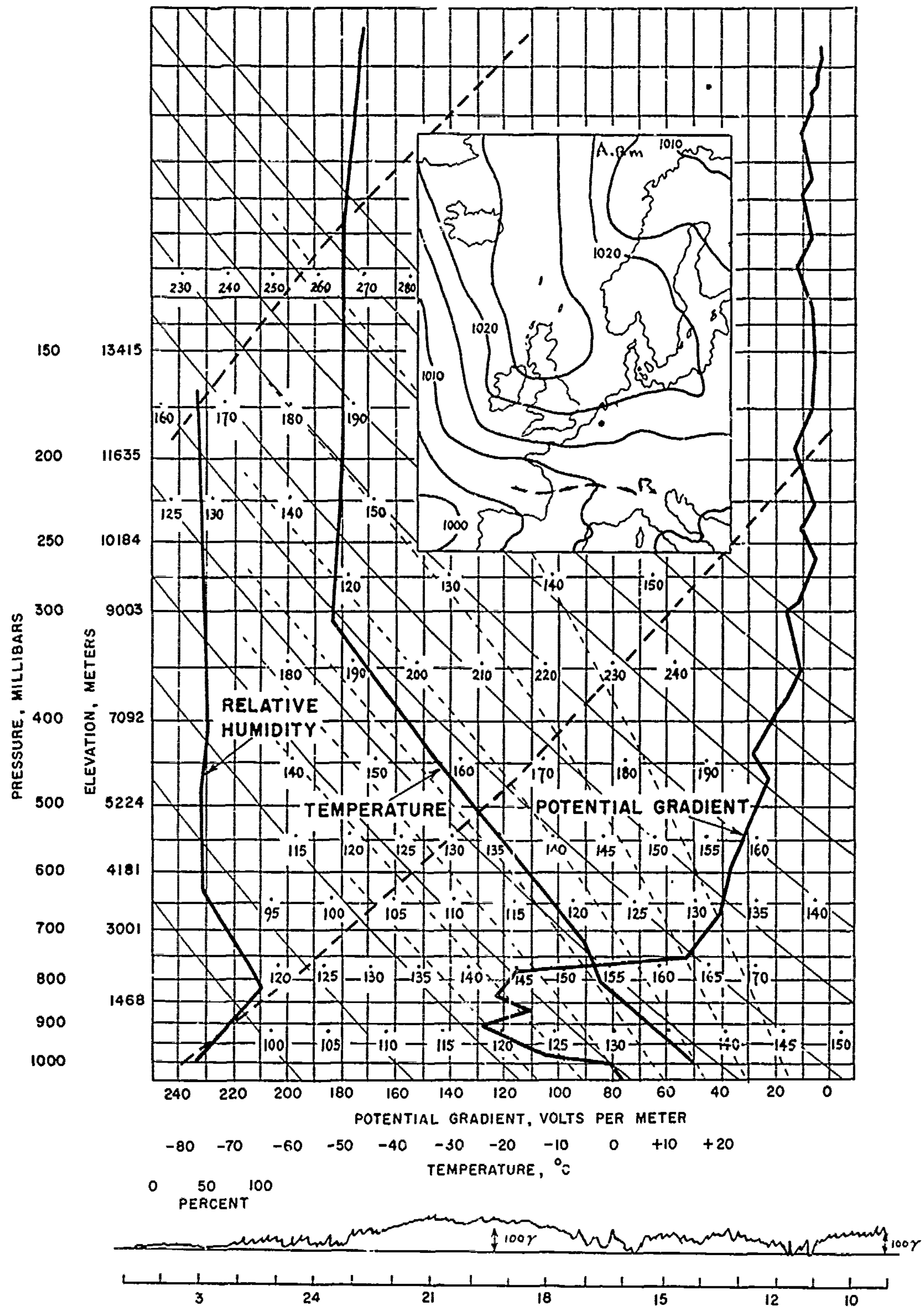


Fig. 1--Data for April 26, 1954, at 14h 00m, 0.1 cloud cover, on a nice day

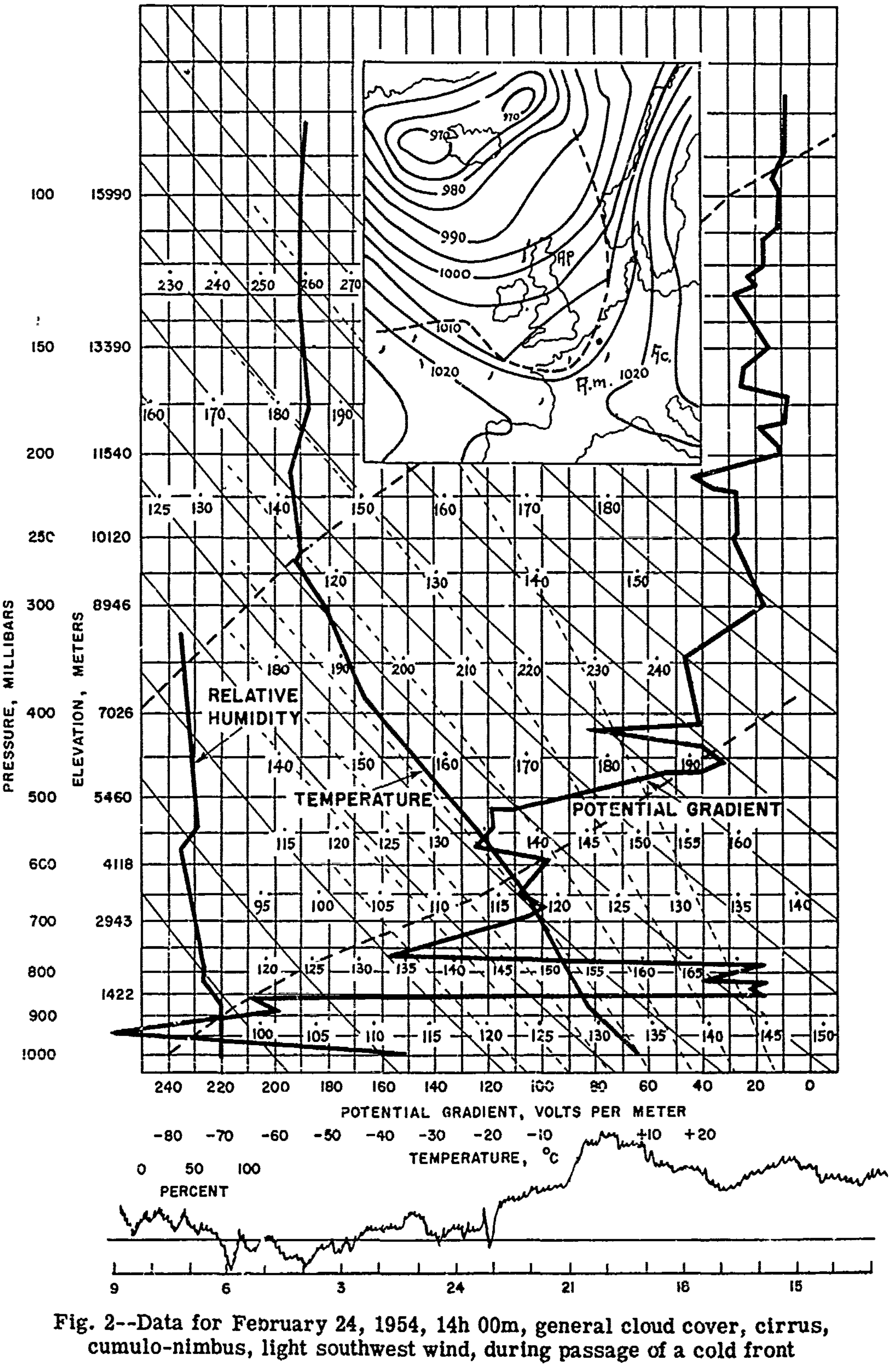


Fig. 2--Data for February 24, 1954, 14h 00m, general cloud cover, cirrus, cumulo-nimbus, light southwest wind, during passage of a cold front

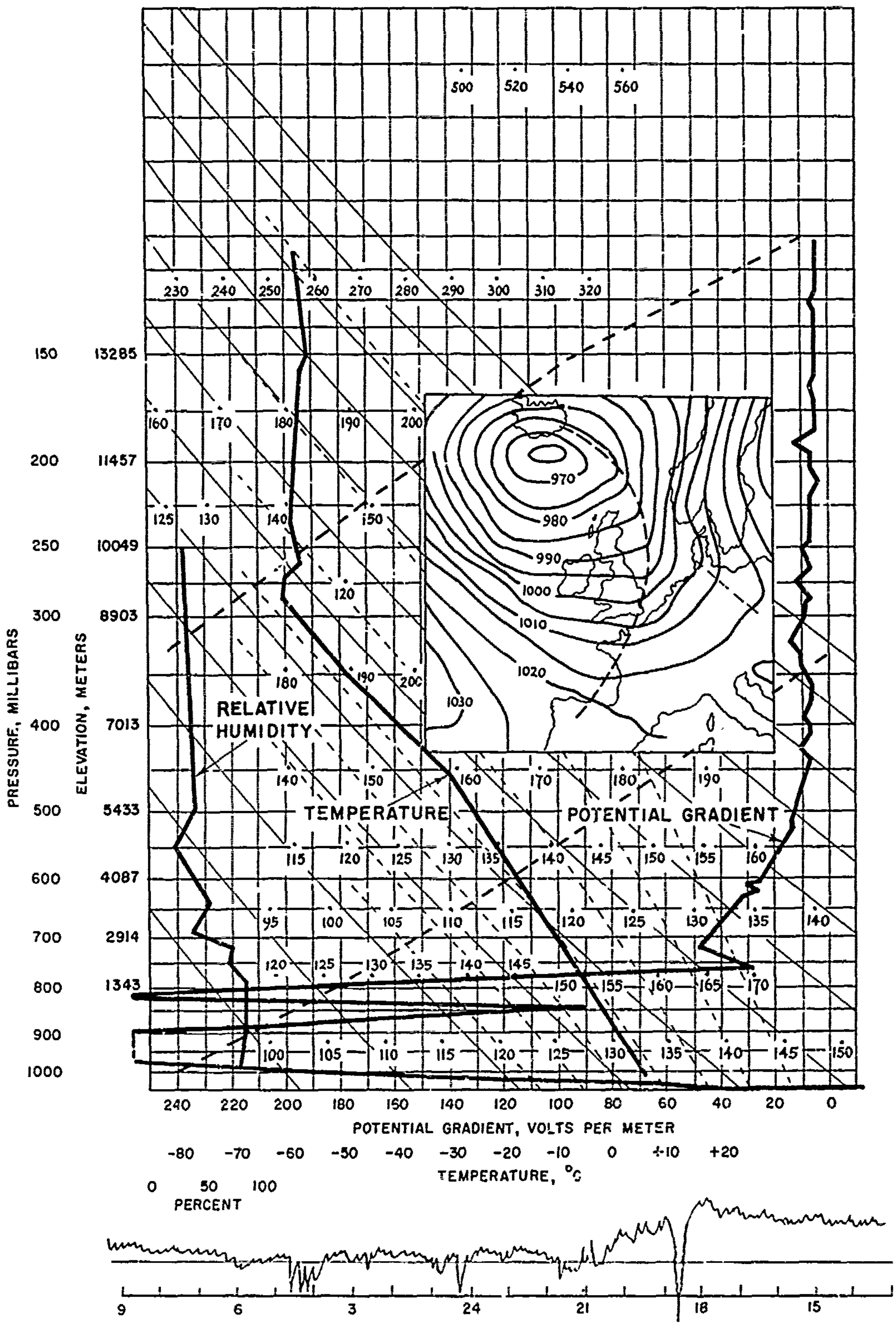


Fig. 3--Data for February 25, 1954, 02h 00m, cover strata cumulus, intermittent rain, light south southwest wind

General conclusions--The following conclusions are reached:

(1) The potential gradient increases in general from the ground up to the first cloud layer, at which level the maximum is reached.

(2) Even if the sounding apparatus passes through a calm region, the maximum in the potential gradient is always located at the level of the lowest clouds.

(3) The positive field existing between the ground and the lowest cloud layer is probably due to the air masses in the upper atmosphere since we find the same charge during our night soundings, which often go to even greater height whereas equilibrium seems to be established in the upper layers where the potential gradient is smaller and less disturbed. It seems that the potential gradient reaches equilibrium near the ground.

(4) At altitudes higher than the stratosphere, there is often a slight increase in the potential gradient and the variations are very weak, between zero and ten volts per meter.

(5) An increase, often very marked, of the atmospheric potential gradient has been observed at a temperature of about -32°C, but less frequently at -40°C.

(6) The air mass markedly influences the value of the potential gradient.

The importance of the potential gradient from the meteorological point of view--We may ask whether the atmospheric potential gradient is an important factor from the point of view of weather prediction.

(1) It is certain that the potential gradient plays a more important role in Belgian Congo than in Europe, for in Africa almost all the rains arise in connection with convective storms and moreover the different masses of air do not seem to be so marked as in Europe. Perhaps the atmospheric potential is a distinguishing factor.

(2) From our soundings at Uccle we can hardly draw any conclusions regarding weather prediction as we have made observations only at one location. A number of soundings carried out over a large region could perhaps reveal some interesting phenomena such as the arrival or change of an air mass as well as equilibrium and turbulence phenomena in the atmosphere.

Continuous measures as a function of altitude--Since it appears that the potential gradient is more stable around 2000 m (where dust, turbulence, haze, etc. would be of less importance), it would be interesting to make continuous measures of the electric field as a function of altitude using radio soundings from a captive balloon.

These measurements would give a better picture of the undisturbed electric field near the ground. We hope to carry out such a program in Belgium in the near future; unfortunately it will not be possible to send up a captive balloon higher than 500 to 600m. It would be interesting to make some observations at 500 m above a mountain where one would have ideal conditions. In Belgium this is impossible since the altitude of the highest point (a plateau) is only 700 m.

References

KOENIGSFELD, L., Investigations of the potential gradient at the Earth's ground surface and within the free atmosphere, in Thunderstorm Electricity, Ch. 3 (H. R. Byers, ed.), Univ. of Chicago Press, 1953.

KOENIGSFELD, L., and PH. PIRAUX, Un nouvel èlectromètre portatif pour la mesure des charges èlectrostatiques par système electronique, Mem., v. 45, Inst. R. Met. Belg., 1951.

AIRCRAFT INVESTIGATION OF THE LARGE-ION CONTENT AND CONDUCTIVITY OF THE ATMOSPHERE

Rita Callahan Sagalyn and Gerard A. Faucher

Air Force Cambridge Research Center
Air Research and Development Command
Cambridge, Massachusetts

Abstract--Recent simultaneous measurements of electrical conductivity, large-ion concentrations, temperature, and humidity in the altitude range 700 to 15,000 ft by means of aircraft are described. The results of forty flights show that over continental areas in fair weather there exists a layer adjacent to the ground varying in depth from 1000 to 10,000 ft in which the vertical distributions of charged nuclei and electrical conductivity are controlled primarily by atmospheric turbulence. At the upper boundary of this layer there is observed a sharp decrease in temperature gradient and in a transition region approximately 800 ft in depth, the conductivity is found to increase by a factor of 1.5 to 6.0; the large-ion content to decrease by a factor of 1.5 to 100. Above this transition region the large-ion content is reduced to very low values and the electrical conductivity increases with altitude in the same manner as determined from earlier experiments. Analysis shows that the surface layer can be identified with the friction layer familiar to meteorologists. The role of atmospheric turbulence and the effect of these results on our understanding of the columnar resistance of the atmosphere are discussed.

Introduction

The observations described in this paper are a continuation and extension of an investigation of the electrical properties of air in the troposphere described in a previous paper [CALLAHAN and Others, 1951]. It was shown there that above the first few kilometers the electrical conductivity of the air is a result of the existence of equilibrium between the production of small ions by cosmic radiation and their destruction by recombination. The conductivity in the lowest part of the atmosphere was found to be less than would be expected from cosmic ray activity data which indicated that destruction of small ions by combination of small ions with charged and uncharged nuclei becomes an important factor in determining equilibrium. It was, therefore, decided to investigate the concentration of charged nuclei (large ions) and to determine the factors controlling their distribution in the atmosphere. Electrical conductivity, temperature, humidity, and pressure were also recorded.

Previously, information about the large-ion content of the atmosphere could only be inferred from the results of a limited number of balloon flights on which condensation nuclei were measured. These measurements were carried out principally by WIGAND [1919]. LANDSBERG [1938] has summarized the data available on the vertical distribution of nuclei in the atmosphere. The results show a rapid decrease in concentration with altitude in the first few kilometers; the concentration at 10,000 ft being only a few per cent of the surface value.

Knowledge of the large-ion content of the atmosphere is not only necessary for the investigation of the processes involved in ion equilibrium but is also important to the understanding of the effect of atmospheric turbulence on the electrical properties of the lower atmosphere.

Method of observation

The results of over forty flights are described in this paper. Most of the measurements were carried out on a fixed flight path, 25 miles long, located southeast of Concord, New Hampshire. Several measurements were also carried out on selected flight paths near San Antonio, Texas, and in the mountainous regions of Southern California. In New Hampshire and Texas, locations for the measurements were chosen where the elevation of the surface above sea level was relatively constant (the height of the surface above sea level varied not more than 200 ft) and over which there was believed to be no large source of industrial pollution. All flights in a given area were made over the same fixed flight path.

The aircraft was flown along the chosen flight path making one pass at specified altitudes between 800 and 15,000 ft above ground. The altitude intervals were 1000 to 2000 ft unless the records showed that any of the measured parameters were changing rapidly with altitude in which case the altitude intervals were reduced. The measurements were carried out through all seasons of the year and throughout the day. The discussion of results is limited to those obtained in fair weather, which we define as days on which there was no unbroken cloud layer in the immediate vicinity of the flight path to inhibit the development of the daily turbulent cycle.

Apparatus

Instrument installation--Instruments were installed in a B-17 aircraft to measure and record simultaneously electrical conductivity, temperature, pressure, relative humidity, air speed, large-ion concentration, and the air flow through the large-ion apparatus. In order to measure these parameters continuously in flight with only one operator, it was found essential to use automatic recording and a central control system.

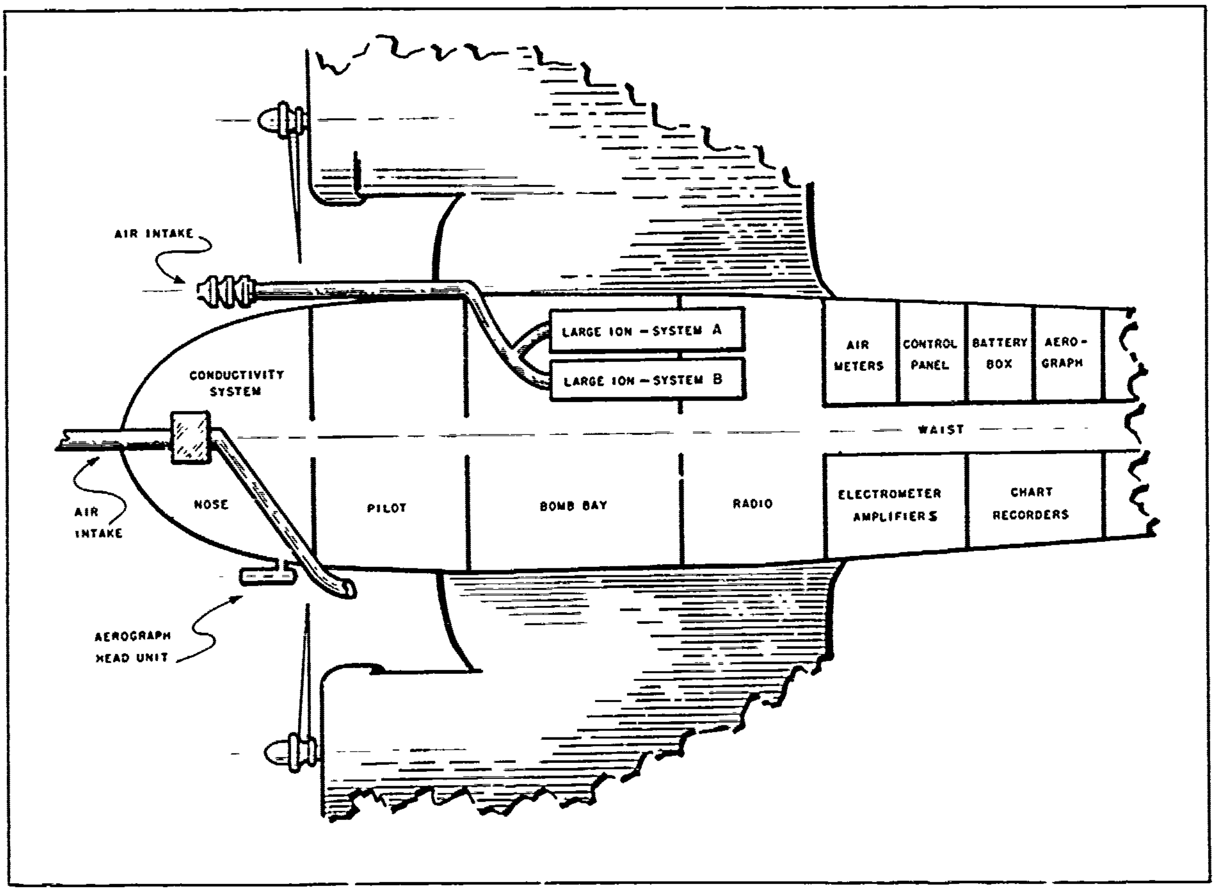


Fig. 1--Arrangement of apparatus on aircraft

A general view of the arrangement of the instruments on the aircraft is shown in Figure 1. All power lines, timing circuits, etc., pass through the main control panel. Four chart recorders, electrometer amplifiers, battery boxes and the control panel, located near the rear of the fuselage, are positioned so that the operator can control and check the operation of all instruments. A four-switch Haydon Timer is used to synchronize all records by placing a timer signal on each record at ten-minute intervals. The air-flow through each ion counter is shut off by means of remotely

controlled valves in order to obtain absolute zero and to check for insulation leakage. It has been found necessary to shock-mount all electrometers, recorders, conductivity and large-ion chambers.

Electrical conductivity measurements--The electrical conductivity of the atmosphere was measured with a cylindrical condenser system, based on principles first outlined by GERDIEN[1905]. A description of the apparatus used in these experiments is given in CALLAHAN [1951]. In the experiments under discussion the cylindrical condenser and the electrometer preamplifier are located in the nose of the aircraft while the electrometer amplifier, recorder and batteries supplying a constant direct current potential to the conductivity chamber were located in the waist compartments. Using the results of our earlier experiments in which it was found that above a few hundred feet $\lambda_+/\lambda_- = 1 \pm 0.1$, the electrical conductivity produced by ions of only one sign is measured.

Meteorological parameters--The temperature, pressure, relative humidity as well as the airspeed of the aircraft are measured and recorded with an Aerograph System developed at the Air Force Cambridge Research Center [GUSTAFSON, 1954]. It consists essentially of a temperature and humidity transmitter mounted on the nose of the aircraft, a pressure and air speed transmitter, and a five-channel graphic recorder for continuously recording these variables, which is mounted in the waist. The fifth channel is used for an automatic time signal. The temperature and relative humidity sensing elements are, respectively, a thermistor bead and a carbon coated strip.

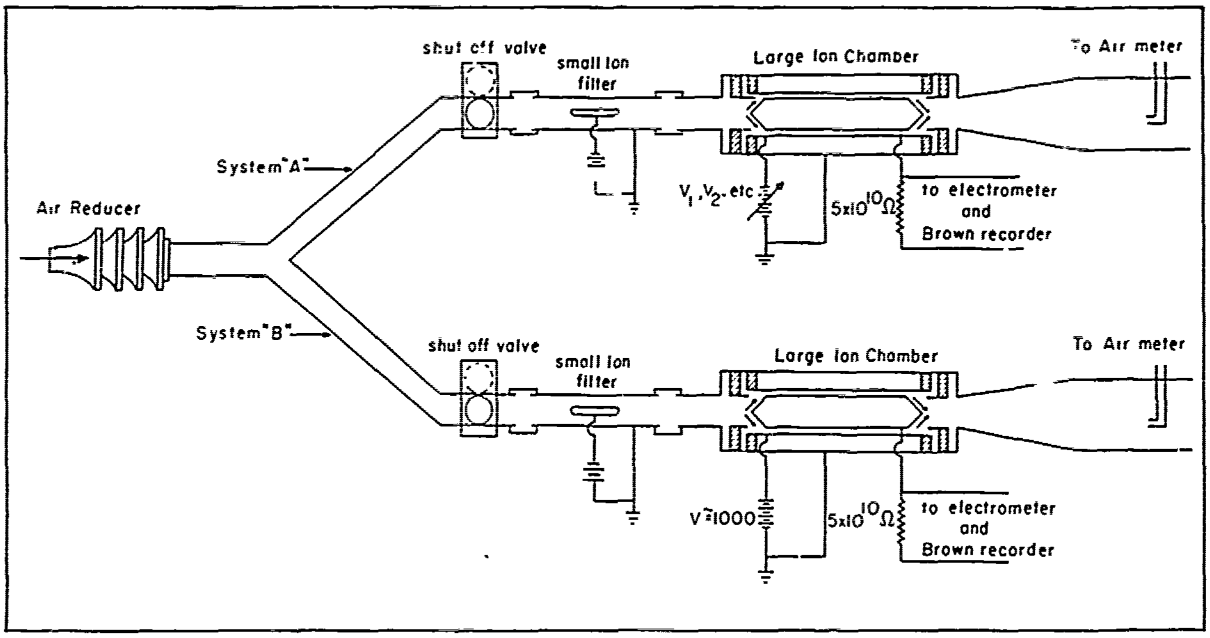


Fig. 2--Schematic diagram of large-ion apparatus

Measurement of concentration--A schematic diagram of the apparatus used for measuring large-ion concentrations is shown in Figure 2. The air sample enters the system through a louvred intake designed to reduce the airflow to approximately four litres per second while maintaining laminar flow. This intake is located near the nose of the aircraft approximately six ft in front of the propellers. The air sample is then passed into the ion counting instruments located in the bomb bay through a brass tube two inches in diameter. In the bomb bay the airstream is first passed into a Y pipe section which divides the air flow in half and then passes through two identical systems in parallel. In each system the airstream is first passed through an electrostatic filter which removes all ions with mobility greater than 0.7 cm^2/sec volt. The air sample next passes through the 'large-ion counter,' then into an output tube, and is finally exhausted into the radio compartment. The velocity of air through the instrument is measured with a Hastings Precision Thermal Anemometer Probe mounted in the output tube. The output of this instrument is recorded on a two-channel Brown

Electronik Recorder. The special advantage of the Hastings Air Meter for air flow measurements in the free atmosphere is that the correction which must be applied for density variations with altitude can be easily determined.

The large-ion counter used in these experiments is essentially the same as the one designed by TORRESON and WAIT [1934] for surface measurements with special modifications for aircraft use. It consists of three concentric insulated cylinders approximately one meter long. The air stream passes between the central and intermediate cylinders 1.27 cm apart, made of highly polished stainless steel. A dc voltage is applied across the intermediate and outer (grounded) cylinders. The central cylinder is connected to ground through a resistance of the order of 10^{10} ohms. The voltage developed across this resistance, determined by the rate at which charged particles in the air stream are drawn to the central cylinder under the influence of the applied electric field, is measured with a vibrating reed electrometer and recorded on a Brown Recorder. By suitably adjusting the air flow and applied potential all charged particles in the air stream of either sign with mobility greater than 2.0×10^{-4} cm^2/sec volt can be measured with this instrument.

If the atmospheric ions were distributed in such a way that there were no ions with mobility less than the limiting mobility of this instrument, the measurement of large-ion concentrations would be relatively simple. With the airflow and applied potential adjusted to obtain 'saturation' for the instrument, the large-ion content may be obtained from the relation

$$i = WNe \qquad (1)$$

where i is the electrometer current, W the airflow through the system, e the charge per ion, and N the concentration of large ions of one sign. However, in agreement with results reported by ISRAEL [1933], SIKSNA [1952], and others, preliminary laboratory experiments showed the existence of atmospheric ions with mobility lower than the limiting value for this instrument. For this reason the theory developed by ISRAEL [1931] is applied to determine the concentration of atmospheric ions from the current-voltage characteristic of the large-ion chamber. Israel's analysis shows that if the concentration of atmospheric ions remains constant during the period of measurement which in our experiments is approximately 20 minutes, then the concentration of charged particles of one sign in the mobility range k_g to ∞ is given by

$$\int_{k_g}^{\infty} dn = Z - VdZ/dV \qquad (2)$$

where dn is the ion concentration in the mobility range k to k dk. The limiting mobility k_g is obtained from the relation $k = W/4\pi CV$, where W is the airflow, V the maximum applied potential and C is the capacitance of the chamber. With $Z = i/We$ plotted versus V the applied potential (2) is the equation of a straight line which is tangent to the Z versus V curve at the value of V corresponding to k_g and which intercepts the ordinate at the point $\int_{k_g}^{\infty} dn$.

In the free atmosphere the concentration of large ions is seldom constant, although the fluctuations at constant altitude were often found to be less than at the surface. If the ion spectrum does not vary significantly during the period of measurement, errors introduced in the current-voltage characteristic due to varying ion content can be eliminated with the experimental arrangement described above. The voltage on one of the two large-ion chambers in parallel is varied in arbitrary steps while on the second, the 'reference system,' a constant potential is maintained. A characteristic independent of the absolute number of ions is obtained by plotting Z/Z_0 versus V; $Z_0 = i_0/W_0 e$ is obtained from the reference system. The analysis is essentially unchanged by this modification. Thus, the total ion concentration in the mobility range 2×10^{-4} to 0.7 cm^2/sec volt, which we will refer to as the large-ion concentration, is equal to the value of the ordinate at the point where the tangent intercepts the ordinate times the average value of Z_0. (All ions in the mobility region 0.7 cm^2/sec volt to ∞ are removed with the electrostatic filter.)

The maximum experimental error in the measurement of electrical conductivity is ±6 pct; relative humidity ±7 pct; temperature ±1°C. The experimental error in the large ion measurement due to the accuracy with which circuit parameters can be determined is ±7 pct. To this must be added an error which is a function of the magnitude of the large-ion concentration; the error in the ratio Z/Z_0 is only a few per cent for concentrations above 1000 per cc and approaches ten per cent for concentrations of the order of 200 per cc.

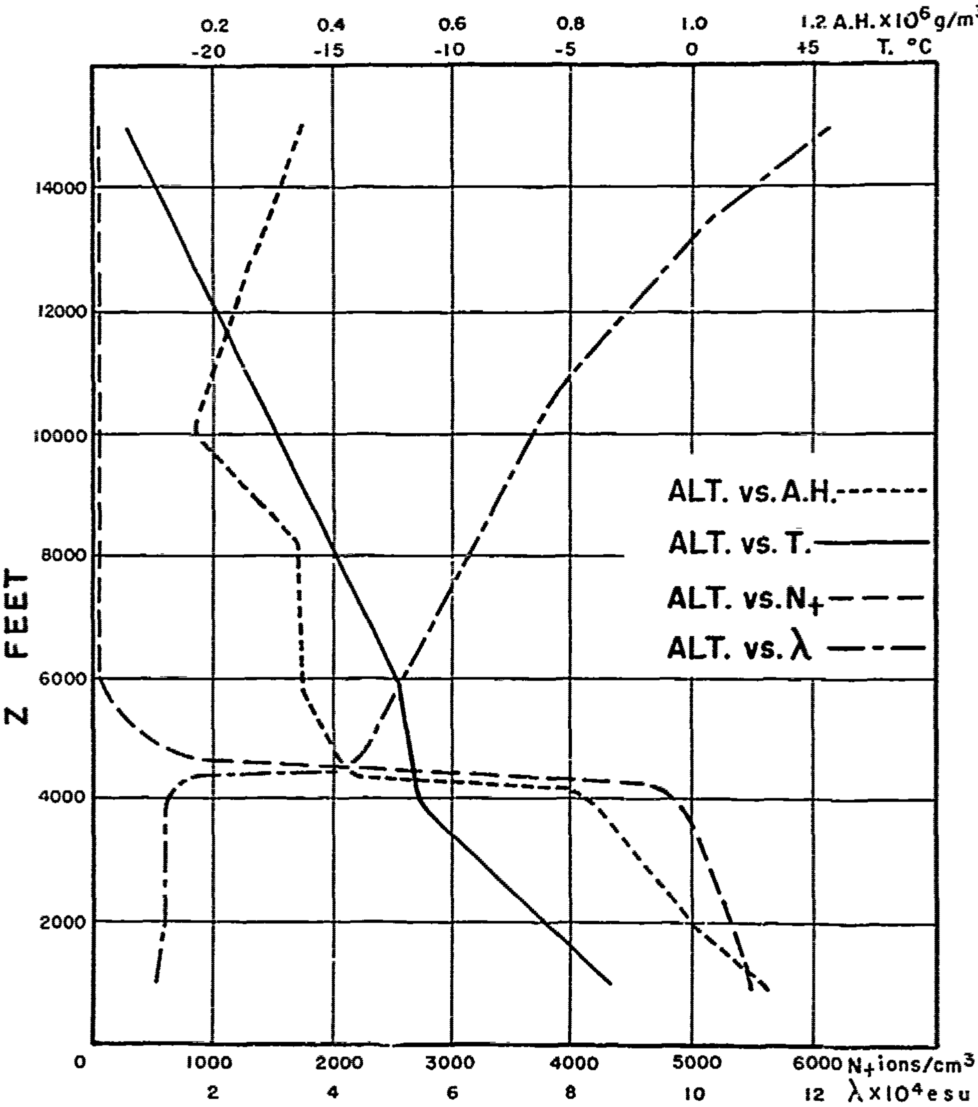


Fig. 3--Variation of absolute humidity (A.H.), temperature (T), positive large-ion concentration (N_+), and total electrical conductivity (λ) with altitude above sea level (Z), February 18, 1953, Bedford, Massachusetts - Sebago, Maine, local time, 11h 00m - 15h 00m

Observations: Variation with height

General description--In Figures 3, 4, 5, and 6 are shown the variation with altitude of electrical conductivity, positive large-ion content, temperature, and humidity observed on four flights. The most striking characteristics of the vertical distribution of the measured parameters which

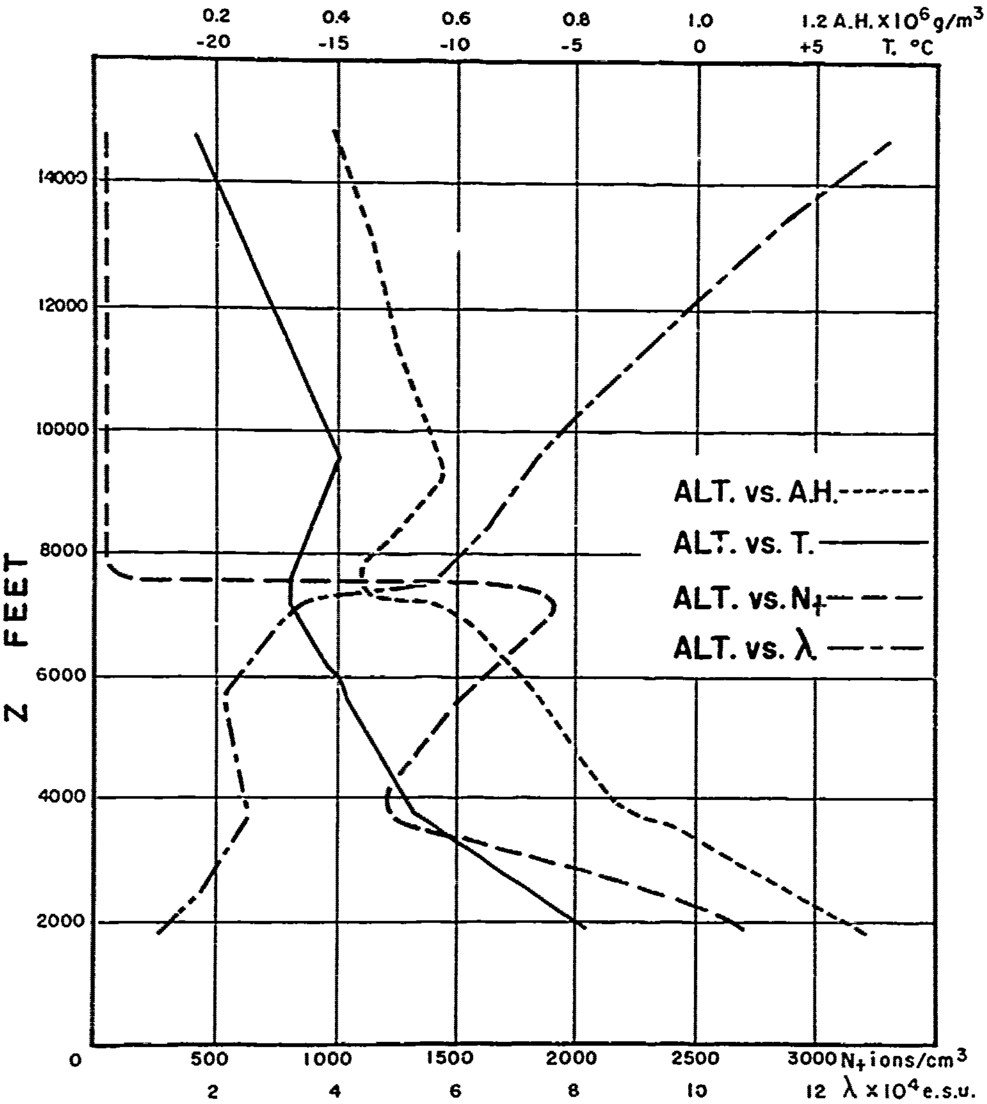


Fig. 4--Variation of absolute humidity (A.H.), temperature (T), positive large-ion concentration (N_+), and total electrical conductivity (λ) with altitude above sea level (Z), January 5, 1953, Bedford, Massachusetts - Sebago, Maine, local time, 12h 30m - 17h 15m

have been observed on all fair-weather flights are shown on these curves. The results show that in fair weather over continental areas the troposphere is divided into two layers with distinct electrical characteristics. The lower layer is characterized by high large-ion content, high humidity, and low electrical conductivity. At constant altitude in this layer the small-ion content deduced from conductivity measurements is approximately inversely proportional to the large-ion content. The conductivity, large ion, temperature, and humidity records show that the horizontal variations of these parameters tend to decrease with altitude, except in the vicinity of the top of the layer where large fluctuations are usually observed. Hereafter, this lower region will be referred to as the exchange (austauch) layer. The depth of the exchange layer has been found to vary from 1000 to 10,000 ft in the course of this investigation.

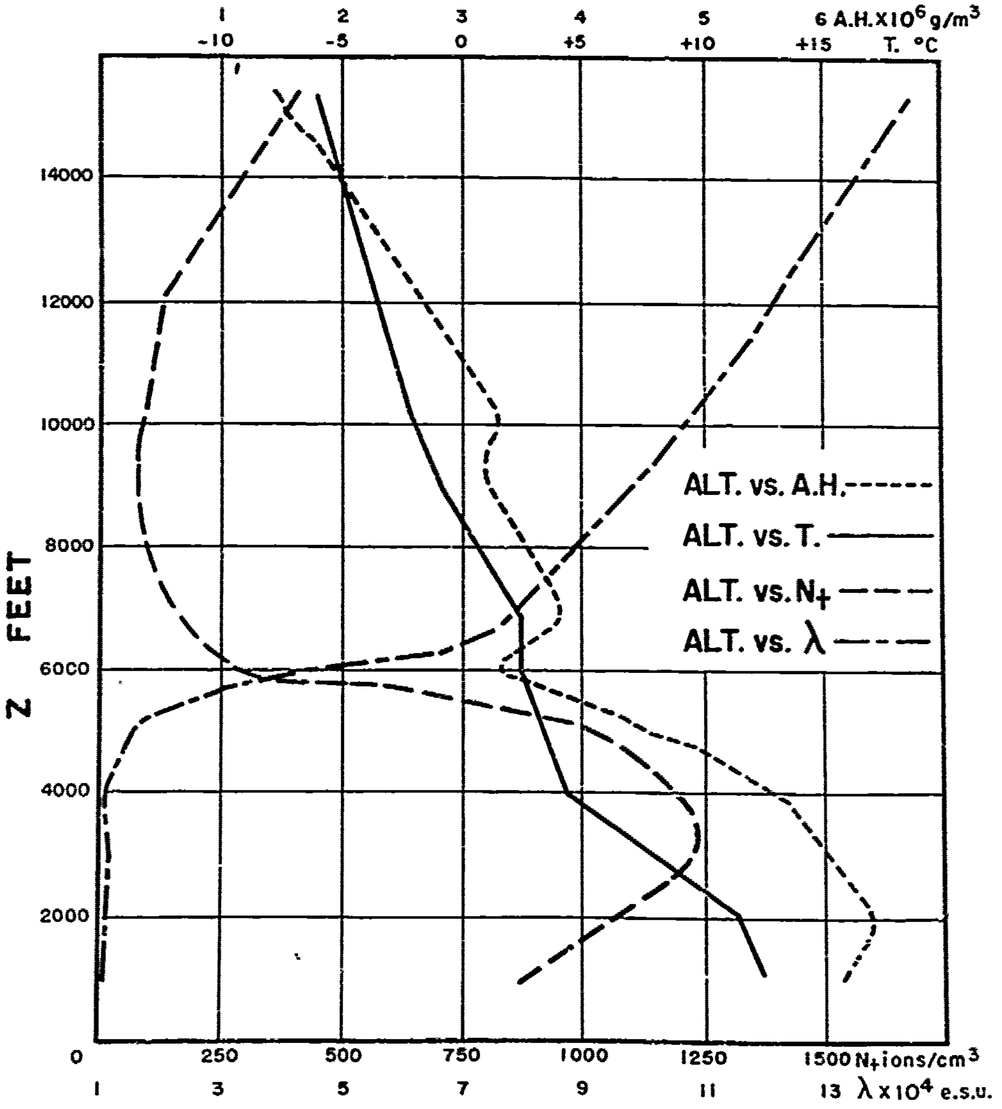


Fig. 5--Variation of absolute humidity (A.H.), temperature (T), positive large-ion concentration (N_+), and total electrical conductivity (λ) with altitude above sea level (Z), November 8, 1953, Concord, New Hampshire - Dover, New Hampshire, local time, 16h 40m - 18h 25m

At the top of the exchange layer a change to a more stable temperature lapse rate is observed, which sometimes consists of an inversion. In a transition region varying in depth from a few hundred to a few thousand feet there is observed a sharp change in the large-ion concentration, electrical conductivity, and humidity. During the course of these experiments the total conductivity has been found to increase in this region by factors ranging from 1.5 to 6 and the positive large-ion content has been found to decrease by a factor of 1.5 to 100. Horizontal variations of the electrical properties and humidity reach a maximum in this region. Passing upward through this region a noticeable decrease in mechanical turbulence is also observed throughout the daylight hours. This is noted by a pronounced decrease in the random tossing of the aircraft and also by a sharp decrease in the instantaneous fluctuations about the mean in the aerograph air speed records. Above this transition region, the large-ion content is reduced to very low values often close to zero, and the electrical conductivity increases rapidly with altitude in the same manner as determined from earlier experiments.

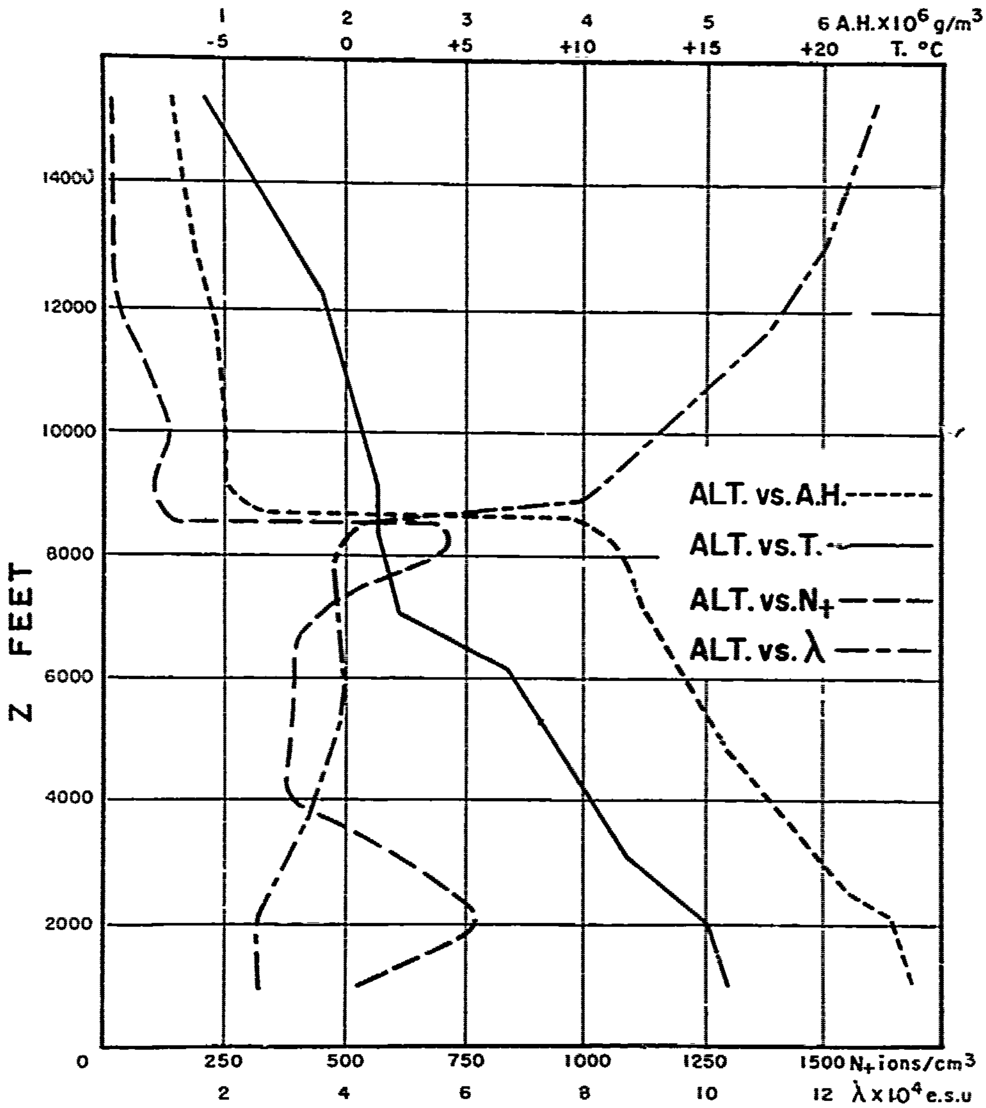


Fig. 6--Variation of absolute humidity (A.H.), temperature (T), positive large-ion concentration (N_+), and total electrical conductivity (λ) with altitude above sea level (Z), August 18, 1953, Dover, New Hampshire - Raymond, New Hampshire, local time, 09h 20m - 11h 40m

To illustrate the general nature of the distribution described above, the results of conductivity and large-ion measurements obtained on nine flights chosen at random between December, 1952, and August, 1953, over a fixed flight path in New Hampshire are summarized in Figures 7 and 8. As shown on the figures, H, the depth of the exchange layer, varies between 3200 and 9400 ft. In Figure 7, the ratio of the height h at which constant altitude measurements were obtained to the height H of the exchange layer is plotted as a function of the ratio λ_m/λ_c. λ_m is the measured value of conductivity at height h and λ_c is the computed conductivity value assuming equilibrium exists between the production of small ions by cosmic radiation and their destruction by volume recombination. Using the results of Thomson's theory for the volume recombination coefficient, the polar conductivity of

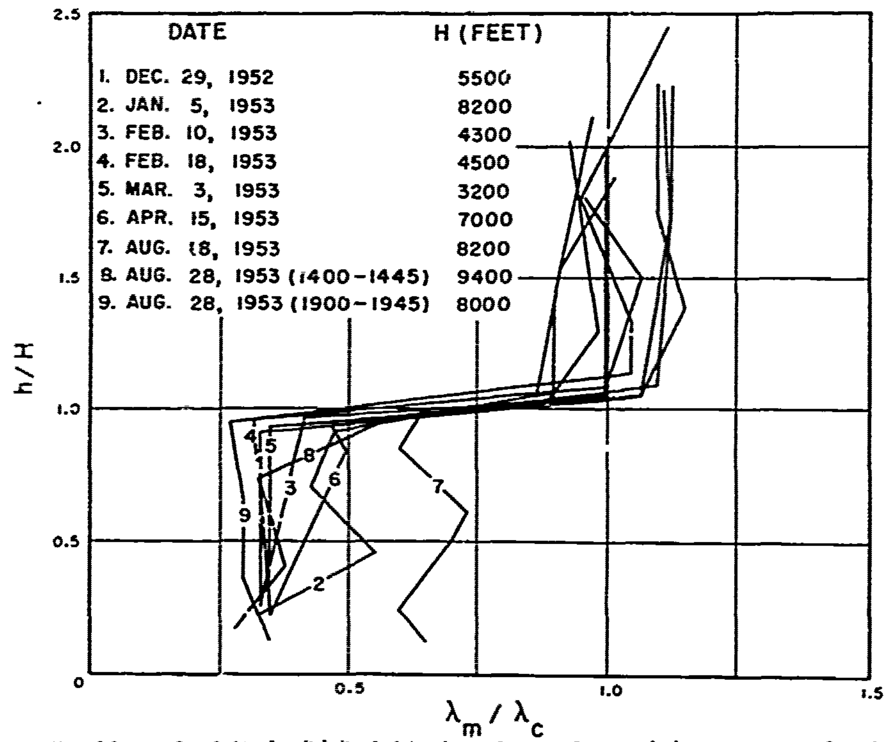


Fig. 7--Aircraft altitude (h)/height of exchange layer (H) versus conductivity measured (λ_m)/conductivity computed from cosmic ray data (λ_c)

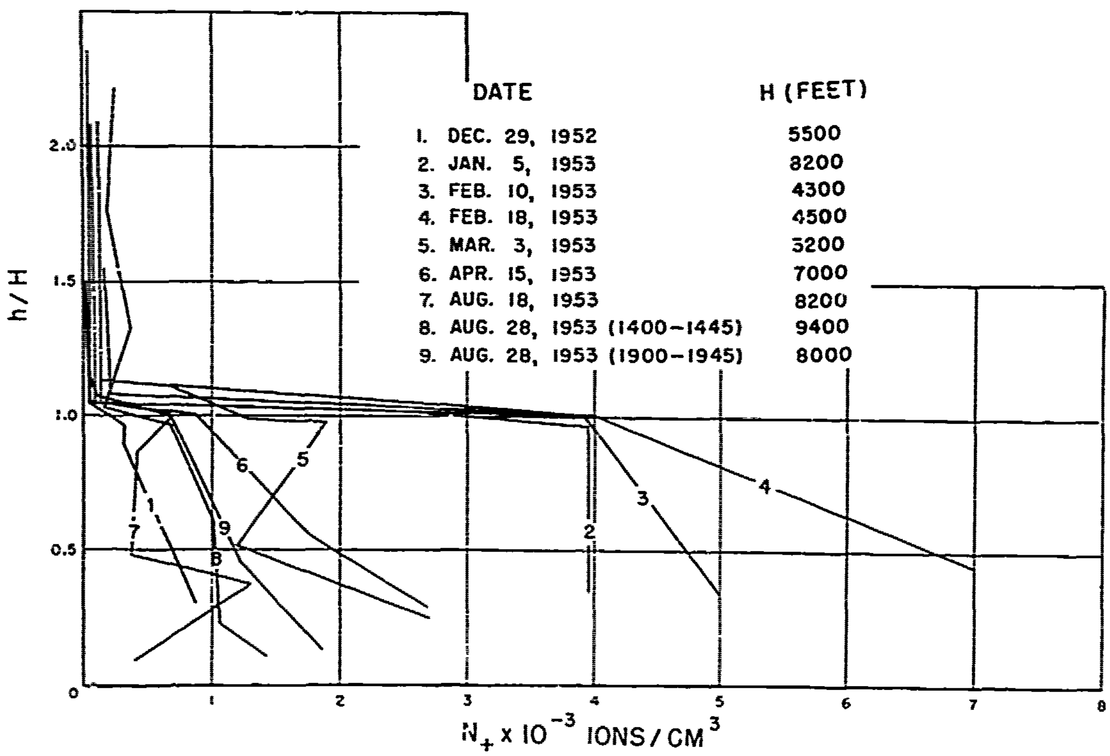


Fig. 8--Aircraft altitude (h)/height of the exchange layer (H) versus positive large-ion concentration (N_+)

air is given by the expression

$$\lambda_c = (ek_0 M^{0.25}/C^{0.5})\,(I_0/\epsilon)^{0.5}\,(P_0/P)^{0.5}\,(T/T_0)^{1.25} \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where e is the charge per ion, k_0 and I_0 are mobility and ionization intensity at normal temperature and pressure, that is, at $T_0 = 273°$ absolute and $P_0 = 760$ mm Hg. M is the average molecular weight of ions in air, C is a constant with the value 1.73×10^{-5} cm^3/sec, ϵ is a probability function which is a function of temperature and pressure. The exact expression for λ_c was used in the present computation because the approximation in CALLAHAN and Others [1951] does not hold with sufficient accuracy below 5000 ft. This manner of representing the results is necessary to illustrate the general features of the distribution because of the large variations in the height of the mass exchange layer from day to day. Above the exchange layer the ratio λ_m/λ_c should approach unity if the simple type of equilibrium assumed in the derivation of (3) exists. The results show a maximum deviation of ten per cent from this value which may be due to statistical fluctuations in cosmic ray intensity or to small variations in the value of the constants used in the computation of λ_c. Large fluctuations in this ratio are to be expected in the exchange layer because of large variations in nuclei content and rate of production of ions from day to day. The results given in Figure 7 show a maximum fluctuation about the mean of approximately 80 pct. In Figure 8, h/H is plotted as a function of N_+, the concentration of positive large ions. The layer-like nature of the conductivity and large-ion distributions in the troposphere is clearly indicated by these figures. The application of these simultaneous large and small ion measurements to a study of ion equilibrium in the exchange layer will be discussed in a later paper.

Variability of profile in exchange layer--Figures 3 to 6 were chosen to illustrate the general features of the vertical distribution of the electrical parameters in the lower troposphere and to show the variability in the height of the exchange layer, in the magnitude of the measured parameters and the complexity of the profile often observed in the exchange layer. In general, the observed profiles can be explained in terms of the vertical temperature distribution and horizontal winds; for example, significant changes in the distribution of charged nuclei are always accompanied by changes in the temperature lapse rate.

Since in the exchange layer, it has been found that variations in conductivity are largely brought about by changes in nuclei content, it is considered sufficient to describe only the charged nuclei distribution in further detail. In this region, the profiles of charged nuclei can be roughly divided into five types which are illustrated in Figures 3 to 8.

(1) Approximately 55 pct of the results show a decrease with altitude to the top of the exchange layer (see Figure 3 and curves 1, 3, 4, 6, 8, 9 of Figure 8). This is usually accompanied by a small increase of λ, a continuous decrease in absolute humidity with altitude and an approximately constant temperature gradient from 1000 ft to the top of the layer.

(2) A nearly uniform distribution with altitude has been observed throughout the exchange layer on about five per cent of the flights (see curve 2 of Figure 8). This type of distribution is accompanied by high winds, intense turbulence, and an adiabatic temperature lapse rate. The conductivity and absolute humidity distributions are similar to type 1. Both types 1 and 2 were usually developed by early afternoon and thus are characteristic of a fully developed turbulent layer.

(3) On approximately ten per cent of the flights there was observed first a decrease, then an increase with altitude to the top of the exchange layer (see Figure 4 and curves 5 and 7 of Figure 8). As shown in Figure 4, the conductivity distribution is roughly the inverse of the large-ion distribution. When this type of distribution was observed a cloud deck often developed later in the day in the region of increase of large-ion content with height.

(4) Several of the late afternoon and evening flights, approximately ten per cent of the total, show first an increase with altitude, then a decrease to the top of the exchange layer (see Figure 5). The temperature gradient is observed to be more stable at lower levels than at intermediate levels. The results suggest that although the source of nuclei has been cut off, enough residual turbulence remains to transport vertically nuclei that have been previously introduced into the atmosphere.

(5) The morning flights, consisting of about 20 pct of the total, generally show the most complicated nuclei distributions. The concentration of nuclei up to the level to which turbulence has penetrated is significantly higher than the concentration at higher altitudes in the exchange layer. That is, properties of the exchange layer determined by the previous history of the air mass are being modified due to the influence of turbulent mixing (see Figure 6). (This example is further complicated by an increase of nuclei at the top of the exchange layer, characteristic of Type 3.) Periodic measurements carried out throughout the day show that when vertical mixing penetrates to the top of the exchange layer, usually by early afternoon, this develops into a distribution of Types 1, 2, or 3.

Table 1--Limits in variation of conductivity and large-ion content

Altitude above sea level	Total conductivity (sec^{-1}) e s u $\times 10^4$			N_+ (no./cm^3)		
	Limits of variation	Mean		Limits of variation	Mean	
		In exchange layer	Above exchange layer		In exchange layer	Above exchange layer
ft						
1,000	0.62- 3.10	1.71	...	496-14,000	2519	...
2,000	0.30- 5.70	1.95	...	131- 7,000	1577	...
3,000	0.32- 6.00	2.45	...	0- 5,700	1250	...
4,000	0.40- 6.38	2.80	4.27	63- 4,887	1139	352
5,000	1.32- 6.70	3.52	5.39	0- 4,120	770	247
6,000	0.80- 7.21	4.45	5.88	0- 3,280	744	156
7,000	1.50- 8.59	4.48	7.14	0- 1,920	480	133
8,000	1.65- 9.52	4.79	7.22	0- 2,320	701	335
9,000	3.75-10.28	5.37	8.57	0- 1,650	353	195
10,000	4.26-11.10	...	8.90	0- 1,200	...	230
12,000	6.92-14.58	...	12.05	0- 875	...	118
15,000	7.38-19.75	...	15.16	0- 2,450	...	275

Limits of variation--The limits of the variation in the electrical parameters, conductivity and positive large-ion content as a function of height above sea level observed during the period of this investigation are shown in Table 1. Along the flight path the elevation of the surface above sea level was approximately 250 ft. The limits of variation in total nuclei content can be obtained by using the experimentally determined value 2.5 for the ratio of uncharged to charged nuclei [LANDSBERG, 1938, p. 210] and in agreement with the results of the present experiments assuming the positive large-ion content equal to the negative. The extreme variability of these parameters in the altitude range 3000 to 9000 ft is partly due to the fact that these levels were sometimes in the exchange layer and sometimes above it. The variation indicated at 2000 ft is representative of the variation at a given level when the results are restricted to data obtained in the exchange layer. The limits of variation above 10,000 ft were 0-500 ions/cc except for three days in August when nuclei penetrated the boundary of the exchange layer. Changes in air mass accounted for some of the largest variations in nuclei content observed on successive days. Arithmetic means of electrical conductivity and positive large-ion content for all observations are also given in Table 1. At altitudes which were sometimes in the exchange layer and sometimes above it, means were computed for these two cases. The average values must be viewed with caution, since the vertical distribution obtained from these values does not give an accurate picture of the profile on individual days.

Variation with area--The general character of the vertical distribution described above is found to be essentially unchanged with area even over mountainous regions. Experiments carried out in the summer months in the mountainous regions of Southern California over peaks up to 14,000 ft above sea level show that the exchange layer exists over mountains but is reduced in depth. The layer in this region was found to vary from a few hundred to 5000 ft in depth. Thus, the records show, for example, the electrical conductivity 1000 ft above a peak 7000 ft above sea level was four times lower than the conductivity 8000 ft above sea level over a valley a few miles away. These results lead us to believe that the large differences between the conductivity values reported by PLUVINAGE and STAHL [1953] at Central Station Greenland, altitude 2.99 km during July and August, 1951, and the results of our earlier measurements at the same altitude in the free atmosphere are due to the fact that the exchange layer extended above Central Station during the period of measurements. During the winter months when convection is greatly reduced, undoubtedly the exchange layer does not penetrate the top of many high mountains; then this important difference between surface and free air measurements will be reduced or entirely eliminated.

These experiments have been carried out through all months of the year. The most significant seasonal trends are an increase in the average height of the exchange layer in the summer months; in New England the average height in January and February was approximately 4500 ft, while in August it extended to approximately 8000 ft. There was also observed a higher nuclei content on the average above the exchange layer in the summer months. Two flights in August show that large ions penetrated the boundary region in the middle of the day as turbulence reached a maximum even though the temperature gradient remained very stable in the vicinity of the boundary.

Discussion of results

Identification with friction layer--The simultaneous measurements of temperature and humidity distributions as well as the information obtained on atmospheric turbulence, described in the last section, show that in general the exchange layer is to be identified with the layer found in many meteorological records which meteorologists refer to variously as the austauch, friction, turbulent, and boundary layer. The layer is characterized by a nearly adiabatic temperature lapse rate with a sharp decrease in lapse rate at the top, uniform specific humidity and in many cases obviously produced by frictional turbulence. It is the layer in which the horizontal wind velocity differs from the wind velocity in the general circulation because of the frictional influence of the surface of the Earth. There are occasions when the boundary of the exchange layer defined as the maximum altitude at which large spatial fluctuations in the electrical properties occur does not coincide with the turbulent layer. For example, in several of the morning flights the exchange layer determined by the previous history of the air mass was found to be continually modified by an unstable turbulent layer.

Application of thermodynamic principles to the observed temperature distribution shows how the upper boundary of the exchange layer acts as a barrier to the vertical transport of nuclei, water vapor, etc. Upward moving elements of air are cooled at the adiabatic lapse rate (approximately one degree C for every 100 meters of ascent) so that as soon as an air sample passes through the top of the exchange layer its temperature is less than its surroundings. The density of the upward moving element will then be greater than that of its surroundings and thus it will sink back to a lower level unless a very strong mechanical force pushes it upward. The same analysis applies for a downward moving element.

Role of atmospheric turbulence--The principal factors controlling the mean state of turbulence in the atmosphere and thus the vertical distribution of nuclei and all physical properties produced at the surface are known from past investigations [MALONE, 1951]. The most important of these are gradient wind velocity, roughness of the surface, vertical temperature distribution and latitude. Results showing the dependence of the profile of the electrical properties on temperature lapse rate and wind velocity were indicated in the last section.

The theoretical investigations of the effect of turbulence on mean motions in the atmosphere by ROSSBY and MONTGOMERY [1935] give a definite upper limit to the layer of frictional influence

which can be written in the form

$$H = C\, W_a/f \ln\left[(z_a + z_0)/z_0\right] \quad (4)$$

where C is a constant, W_a is the total wind velocity at anemometer height z_a, the Coriolis Parameter $f = 2\omega \sin L$, where ω is the angular velocity of the Earth, and L the latitude, z_0 is a length characteristic of the roughness of the ground. Thus, over a region with constant roughness parameter z_0, the height should be proportional to the wind velocity at anemometer level. All data on the height of the exchange layer over the New England flight path has been plotted as a function of wind velocity for the same period obtained from local surface stations to determine whether surface wind measurements can be used to predict the height of the exchange layer for individual days. As shown in

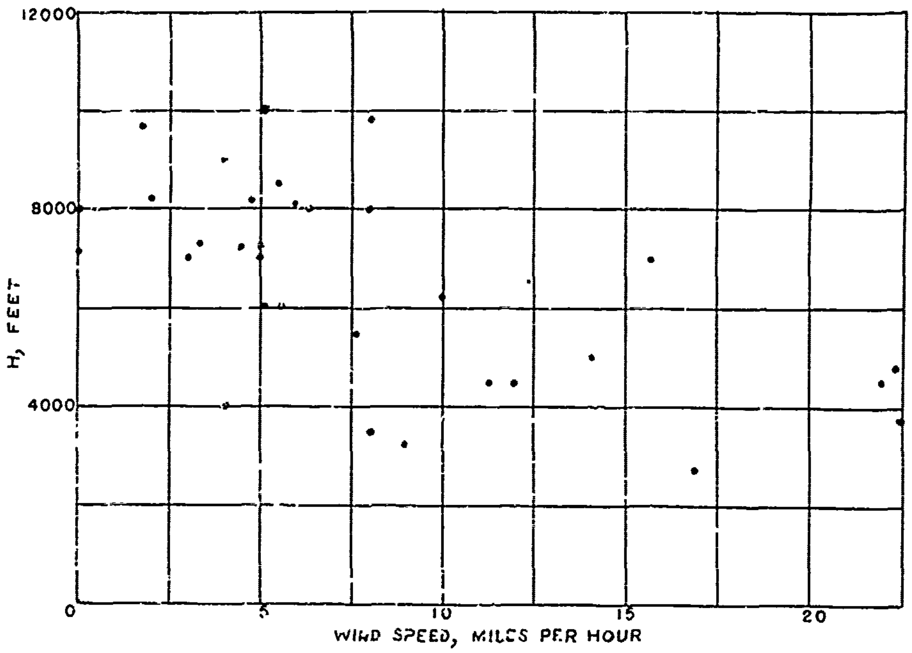


Fig. 9--Height of exchange layer versus surface wind speed

Figure 9, however, a linear relation is not found. This disagreement is probably largely caused by the simplifying assumptions made in the development of the theory where an adiabatic temperature lapse rate and gradient wind direction and velocity, constant with elevation were assumed. Because it was realized that extraneous influences such as large temperature inversions or marked instability at the surface might cause wide scatter of individual results, Rossby and his collaborators used averages of large numbers of observations for the original check of the theory.

These results indicate that interested surface stations could not obtain a reliable estimate for the height of the exchange layer from the Rossby theory. However, comparison of the present results with simultaneous balloon sonde data shows that H can be accurately obtained from temperature and humidity balloon sonde records.

<u>Columnar resistance over continents</u>--It is of interest to consider the effect of these results on our understanding of the columnar resistance of the atmosphere over continents. The resistance R of a vertical column of the atmosphere one cm^2 in cross section extending from the Earth's surface to the height h is equal to $\int_0^h r\, dh$; the atmospheric resistivity $r = 1/(\lambda_+ + \lambda_-)$.

The results of the balloon Explorer II indicated that the total columnar resistance from the Earth to the upper conducting layers was of the order of 10^{21} ohms. The present results give values of R varying from 9×10^{20} to 2.5×10^{21} ohms. R was computed from conductivity values; measured values were used to 15,000 ft and values computed from (3) assuming cosmic radiation the only source of ionization were used at higher altitudes.

Computations of the resistance of a vertical column one cm^2 in cross section from the surface to the top of the exchange layer have been found to vary considerably from day to day and with time of day, and amount to from 40 to 73 pct of the total resistance; the average value was found equal to approximately 60 pct of the total. These results were obtained in a relatively unpolluted area. The contribution of the resistance of the exchange layer to the total in industrial areas must be greater on the average. Variations in the resistivity of the exchange layer brought about by meteorological factors through their control of the vertical distribution of atmospheric nuclei will therefore have a significant influence on the total columnar resistance of the atmosphere even though it is generally restricted to the lowest three kilometers.

As would be expected from the previous discussion, the altitude variation of R computed from conductivity values is subject to considerable variation. The results obtained on three flights chosen arbitrarily are given in Figure 10; the altitude variation of R obtained from the Explorer II results is given for comparison.

The results given above, under Observations, agree qualitatively with the atmospheric model suggested by WAIT [1942] and later employed by Israel to explain atmospheric electric measurements at the ground. Wait assumed that the columnar resistance could be considered as divided into two parts: R_1, a lower component varying with local time, and R_u, a component constant in time. However, the assumptions made in determining the height to which local influences penetrate leads to misconceptions about the electrical characteristics of the atmospheric friction layer. For example, the present experiments show that the height of the layer often varies in a systematic manner through the day and is also found to vary many thousands of feet from day to day in a given season. Furthermore, the assumption that the atmospheric resistivity is constant throughout the exchange layer is not valid in general.

Summary

(1) The height of the exchange layer varies between 1000 and 10,000 ft, with an average value of approximately 6000 ft. It varies with season, reaching a maximum in the summer months.

(2) At all altitudes in the exchange layer, the limits of variation of charged nuclei were greater than an order of magnitude for the days investigated.

(3) The vertical distributions of large ions can be roughly divided into five types which can be explained in terms of atmospheric turbulence, that is, temperature gradient, horizontal winds, etc.

(4) Throughout the exchange layer the small-ion content, and therefore, the electrical conductivity is determined primarily by the magnitude of the nuclei concentration.

(5) Horizontal variations of large-ion content, conductivity, and humidity reach a maximum in the transition region at the top of the exchange layer.

(6) At the top of the exchange layer, a change to a more stable temperature lapse rate is observed.

(7) A sharp change in the magnitude of the absolute humidity, nuclei content and conductivity is observed at the top of the layer.

(8) A reliable estimate of the height of the exchange layer can be obtained from temperature and humidity balloon sonde records. The Rossby theory does not hold with sufficient accuracy for individual days.

(9) In general, the profiles of absolute humidity and charged nuclei are similar.

(10) The exchange layer exists over mountains, though reduced in height.

(11) The exchange layer was found to contribute 40 to 73 pct to the total columnar resistance of the atmosphere.

(12) The exchange layer can be identified with the atmospheric friction layer.

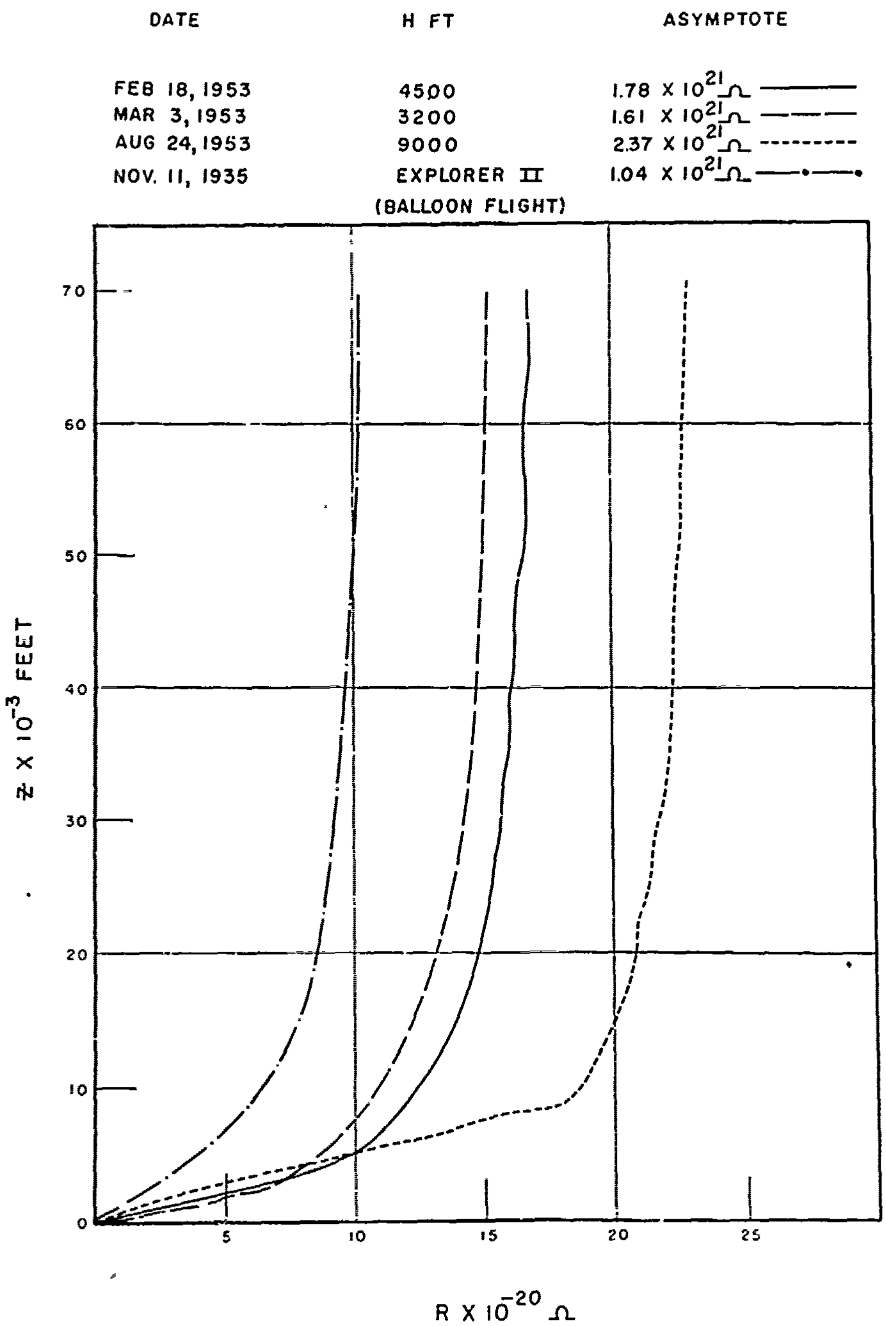


Fig. 10--Resistance (R) of air column 1 cm^2 in cross section as a function of altitude above sea level (Z)

(13) Immediately above the transition region the concentration of charged nuclei of one sign averages approximately 200 ions/cc.

(14) Above the exchange layer the electrical conductivity is determined primarily by the intensity of cosmic radiation, in agreement with earlier experiments.

(15) In the cases examined, the ratio N_+/N_- was found equal to unity on the average with a maximum departure of ± 0.17, in the altitude range 1000 to 15,000 ft.

The authors wish to acknowledge the work of Roland Matson and Maria Mahoney, who assisted in carrying out the experiments and in the analysis of the data. We also thank the personnel of the 6520th Flight Test Squadron, Hanscom Air Force Base, Bedford, Massachusetts, who flew and maintained the aircraft.

References

CALLAHAN, RITA C., and Others, Electrical conductivity of air in the troposphere, J. Geophys. Res., v. 56, no. 4, pp. 545-551, 1951.

GERDIEN, H., Die absolute Messung der spe .ifischen Leitfähigkeit und der Dichte des verticalen Leitungsstromes in der Atmosphäre, Terr ``ag., v. 10, pp. 65-79, 1905.

GUSTAFSON, P., AFCRC Aerograph equipmen. 'nstrumentation for Geophys. Res., no. 3, Air Force Cambridge Research Center, 1954.

ISRAËL, H., Zur Theorie und Methodik der Größenbestimmung von Luftionen, Gerlands Beitr. Physik, v. 31, pp. 173-216, 1931.

ISRAËL, H., and L. SCHULZ, The mobility spectrum of atmospheric ions: principles of measurements and results, Terr. Mag., v. 38, pp. 285-302, 1933.

LANDSBERG, H., Atmospheric condensation nuclei in Atmospheric condensation nuclei monograph, Pa. State College, and Beitr. Geophys. (sup.), v. 3, pp. 155-252, 1938.

PLUVINAGE, P., and P. STAHL, La conductibilité électrique de l'air sur l'inlandsis groenlandais, An. Geophys., v. 9, no. 1, pp. 34-44, 1953.

ROSSBY, C. G., and R. B. MONTGOMERY, The layer of frictional influence in wind and ocean currents, M.I.T. and Woods Hole Oceanog. Inst., Papers in Phys. Oceanog. and Met., v. 3, no. 3, 1955.

SIKSNA, R., Measurements of large ions in the atmospheric air at Uppsala, Arkiv. for Geofysik, v. 1, no. 18, pp. 483-518, 1952.

TORRESON, O. W., and G. R. WAIT, Measurements of total nuclei of uncharged nuclei, and of large ions in the free atmosphere at Washington, D. C., Terr. Mag., v. 39, pp. 47-64, 1934.

WAIT, G. R., Electrical resistance of a vertical column of air over Watheroo (western Australia) and over Huancayo (Peru), Terr. Mag., v. 47, pp. 243-249, 1942.

MALONE, T. F., (Ed.), Energy equations in Compendium of Meteorology, Amer. Met. Soc., pp. 483-509, 1951..

WIGAND, A., Die vertikale Verteilung der Kondensationskerne in der freien Atmosphäre, An. der Physik, v. 59, pp. 689-742, 1919.

CONDUCTIVITY MEASUREMENTS IN THE STRATOSPHERE

C. G. Stergis, S. C. Coroniti, and A. Nazarek

Geophysics Research Directorate, Air Force Cambridge Research Center
Air Research Development Command, Cambridge, Massachusetts

D. E. Kotas, D. W. Seymour, and J. V. Werme

Minneapolis-Honeywell Regulator Co.
Philadelphia, Pennsylvania

Abstract--The electrical conductivity of the atmosphere from ground up to 100,000 ft was measured during a series of five balloon flights made in 1953. The tests indicate that the conductivity of the atmosphere increases monotonically up to the maximum height at which measurements were made. The variation of conductivity with altitude follows closely the variation expected from cosmic ray intensity data. On none of the flights was there a clear indication that the conductivity diminishes in the region of 65,000 ft above sea level as obtained during the Explorer II flight in 1935. We conclude that the phenomenon observed on Explorer II is not a universal one.

Introduction--Prior to 1953, the only measurements, to our knowledge, that were made of the electrical conductivity of the stratosphere were those obtained by GISH and SHERMAN [1936] during the famous flight of the balloon Explorer II in November, 1935. On this flight, the conductivity was found to increase with height until an elevation of 62,000 ft was reached. The conductivity then began to diminish and continued doing so up to 72,000 ft, the maximum elevation attained by the balloon.

This diminution in conductivity could not be explained by Gish and Sherman in a completely satisfactory manner. Their best hypothesis was that the diminution was due to the presence of Aitken nuclei in this region of the stratosphere. But this hypothesis raised even more questions. Why are such large particles found in this region of the stratosphere? Are they formed there or do they originate at the surface of the Earth and ascend to this region? If the former is so, what are the agents responsible for the formation of nuclei? If the latter, what is the mechanism by which nuclei are transported to this region of the stratosphere? And why should this region be favored with the accumulation of nuclei? Is this low conductivity regic ˙:mited between 62,000 and 72,000 ft or does it extend higher into the stratosphere? Also, since only one flight was made, the question is immediately raised as to whether the effect observed on Explorer II is a universal phenomenon or just an isolated case.

This matter lay dormant until 1951 when HOLZER and SAXON [1952] raised some of the above questions in their theoretical paper on the current distribution in the vicinity of thunderstorms. And then in 1953, McDONALD [1953] attempted to account for the presence of nuclei in the lower regions of the stratosphere. He examined the hypothesis that thunderstorm updrafts carry nuclei from the lower levels of the troposphere, where nuclei are plentiful, through the troposphere and inject them into the lower regions of the stratosphere. He concluded that this hypothesis is incapable of explaining the conductivity observations that had been made up to that time.

In an effort to answer some of the questions raised by the Explorer II flight and to extend the measurements of the conductivity of the atmosphere up to 100,000 ft, this investigation was undertaken.

Experimental method--The instrument used for measuring the conductivity of the atmosphere is a modified Gerdien-type chamber which has been described previously [CORONITI and Others, in press]. It consists essentially of two concentric cylinders across which a given voltage is applied. Air passing through this chamber gives up a fraction of its electric charge to the inner electrode which is connected to a dc electrometer-amplifier. This in turn drives a standard radiosonde transmitter operating at 1680 megacycles per sec. The signals from the transmitter are received at the ground and recorded automatically. The following parameters are periodically telemetered: conductivity, temperature, pressure, and certain reference signals used as an indication of the reliability of the instrument.

The conductivity chamber is transported into the stratosphere by means of a single plastic balloon or by a cluster of rubber balloons, the average rate of ascent being approximately 1000 ft/min. At the end of a predetermined time interval, long enough to permit the balloon to reach maximum altitude, the balloon is cut down automatically. The instrument then descends by parachute at a rate which is approximately 7000 ft/min at the beginning of the descent and about 2000 ft/min at the end of the descent.

To minimize the electrostatic effects of the balloon and parachute on the instrument, the conductivity chamber is suspended several hundred feet below the balloon on the ascent and the same distance below the parachute on the descent.

Experimental results--All the flights were made during the daylight hours at Holloman Air Development Center, Alamogordo, New Mexico. Out of a total of eight flights, five were successful. These occurred on July 16, and on October 21, 27, 28, and 30, 1953. The maximum heights attained during these flights were 68,000, 72,000, 82,000, 90,000, and 100,000 ft, respectively. Since the variation of conductivity with altitude during all of the flights was essentially the same, we shall restrict the discussion to the last two flights, the ones which attained altitudes of 90,000 and 100,000 ft, respectively. We shall refer to these as Flights 4 and 5.

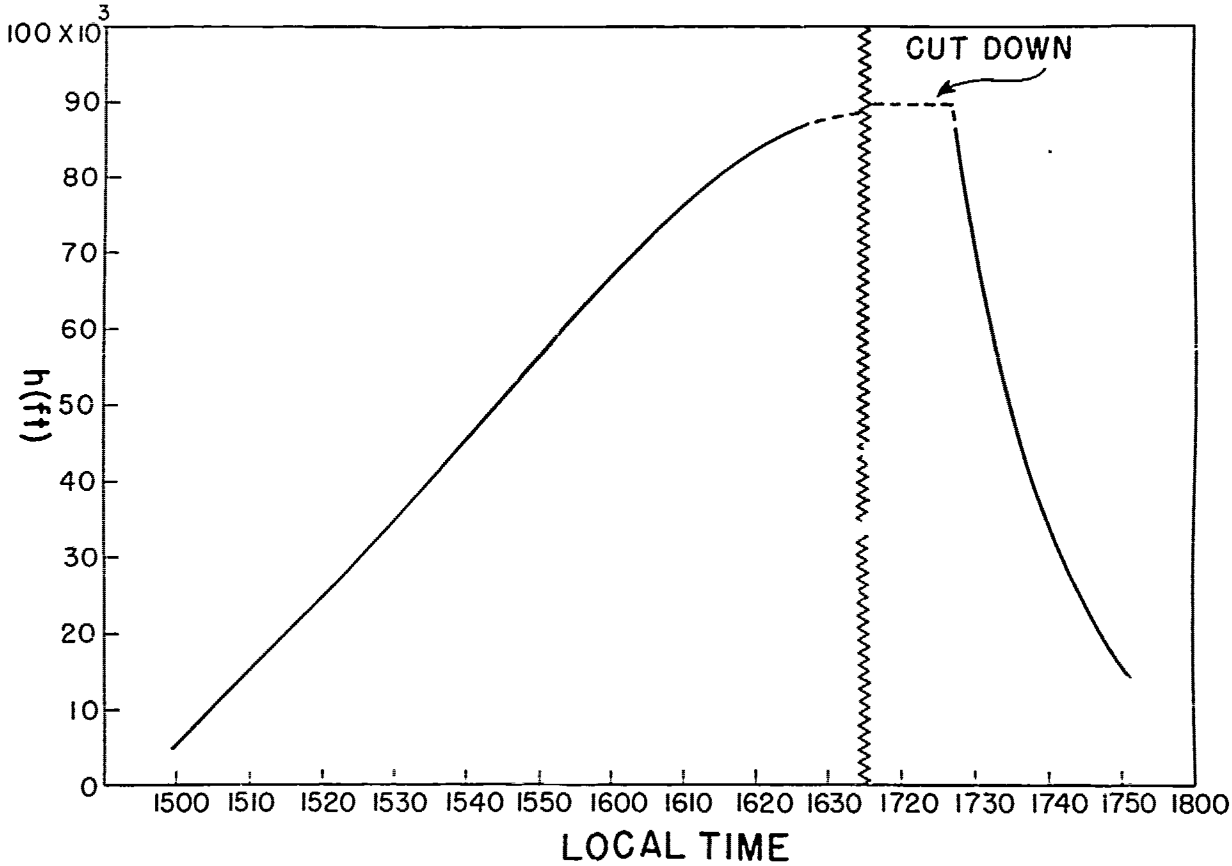


Fig. 1--Time-altitude relationship on Flight 4

On Flight 4 the conductivity chamber was carried aloft by an 80-ft plastic balloon. Figure 1 shows the altitude of the chamber as a function of time. This information is necessary in determining whether the air flow through the chamber is sufficient for proper operation. On this figure,

the altitude values were calculated from the telemetered pressure readings by means of the data of the ROCKET PANEL [1952].

It is observed that the instrument was carried aloft at a fairly constant ascent rate of approximately 1000 ft/min to an altitude of about 70,000 ft. The ascent rate decreased gradually from 70,000 ft to 87,000 ft, where the balloon practically ceased rising. For about an hour the balloon floated at almost constant altitude. At a predetermined time the conductivity chamber was separated from the balloon and descended by parachute. It is observed that the initial descent rate was approximately 7000 ft/min. The descent rate gradually diminished to a value of about 2000 ft/min at the lower levels of the atmosphere.

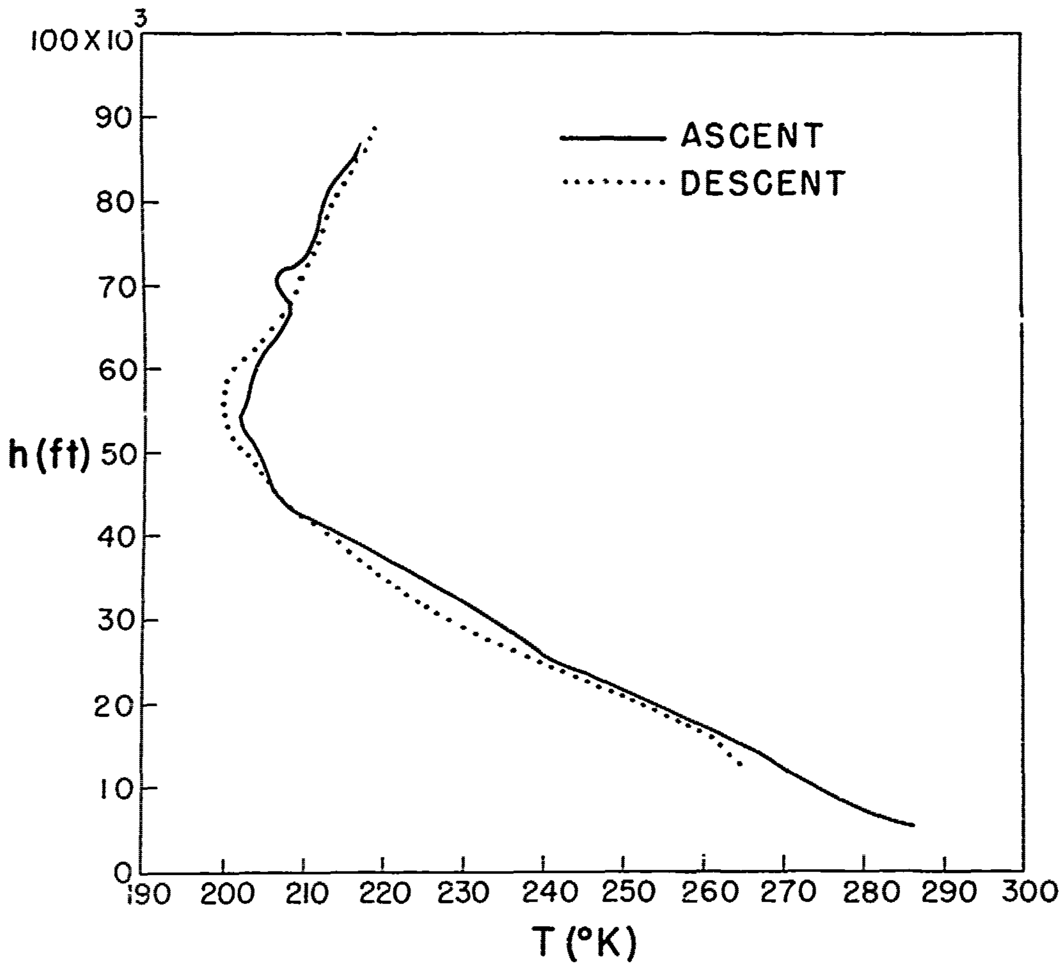


Fig. 2--Altitude-temperature relationship on Flight 4

Figure 2 shows the temperature as a function of height on Flight 4 for both ascent and descent. It is observed that the temperature minimum of approximately 200°K occurs at about 55,000 ft above sea level. The temperature distribution is used in the calculation of the expected conductivity values in the atmosphere as well as in the indication of the height of the tropopause on this particular day. The latter information is of use in the consideration of problems such as the probable distribution of Aitken nuclei in the atmosphere.

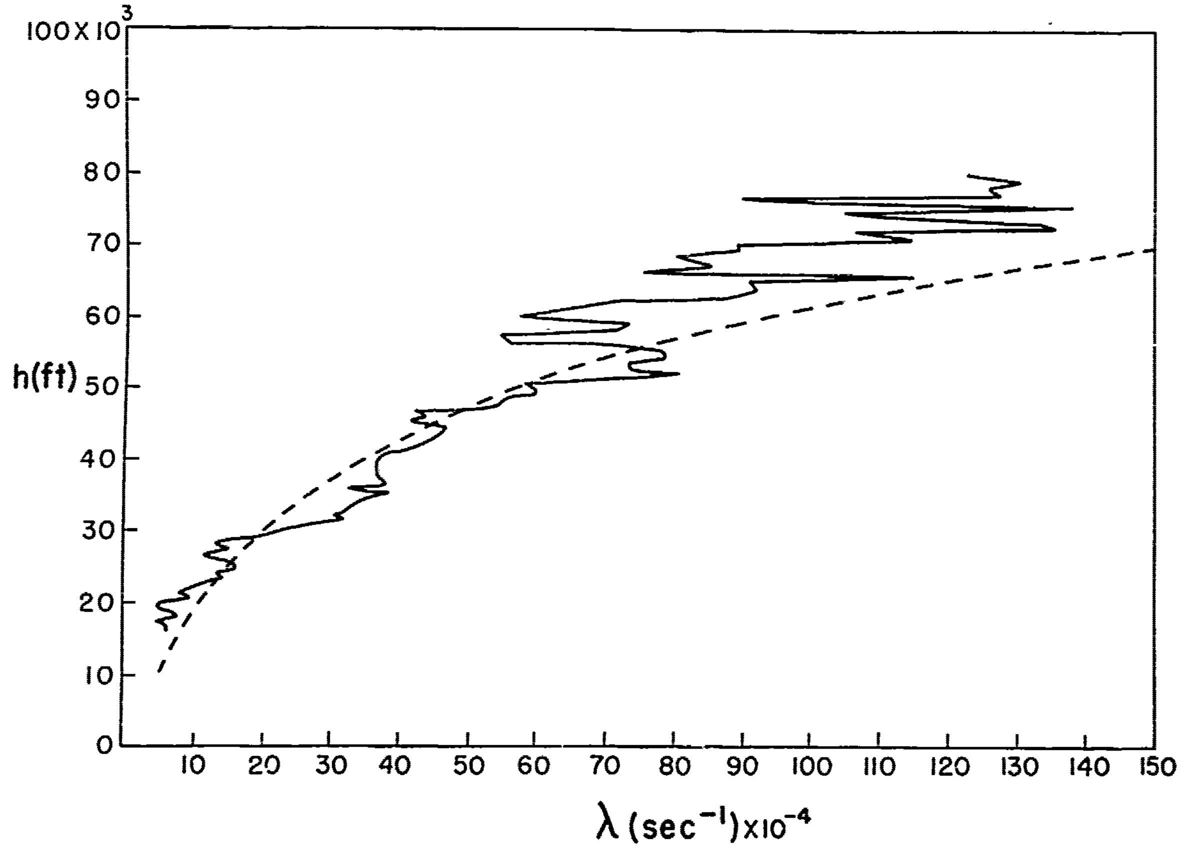


Fig. 3--Relationship of negative conductivity to altitude on ascent, Flight 4 (dashed line represents theoretical curve)

The values of conductivity measured on the ascent of Flight 4 are shown by the solid line in Figure 3. It is observed that, in general, the conductivity increases with altitude but that considerable variations exist. These variations become so pronounced at the higher altitudes that it is impossible to say whether any regions with abnormal values of conductivity exist in the stratosphere. We shall reserve until later the question of whether these fluctuations are due to real phenomena in the atmosphere or to instrumental difficulties.

Figure 4 shows the values of conductivity measured on the descent of Flight 4. The descent data are markedly different from the ascent data, and there is practically no fluctuation in the conductivity values. In fact, the descent curve is so smooth that any regions of abnormally low conductivity would have been detected easily. None were.

On Flight 5 the measured temperature as a function of altitude and the altitude of the balloon as a function of time were very similar to those obtained on Flight 4. Figures 5 and 6 show the measured conductivity values for ascent and descent on Flight 5. The characteristics exhibited by these curves are very similar to those exhibited on Flight 4, shown in Figures 3 and 4. The same characteristics were found on all of the successful flights.

The results of the conductivity measurements may be summarized as follows: (1) In general, conductivity increases with altitude. (2) The values of conductivity measured during the ascent show considerable fluctuation, quite small at the lower elevations but very pronounced at the higher

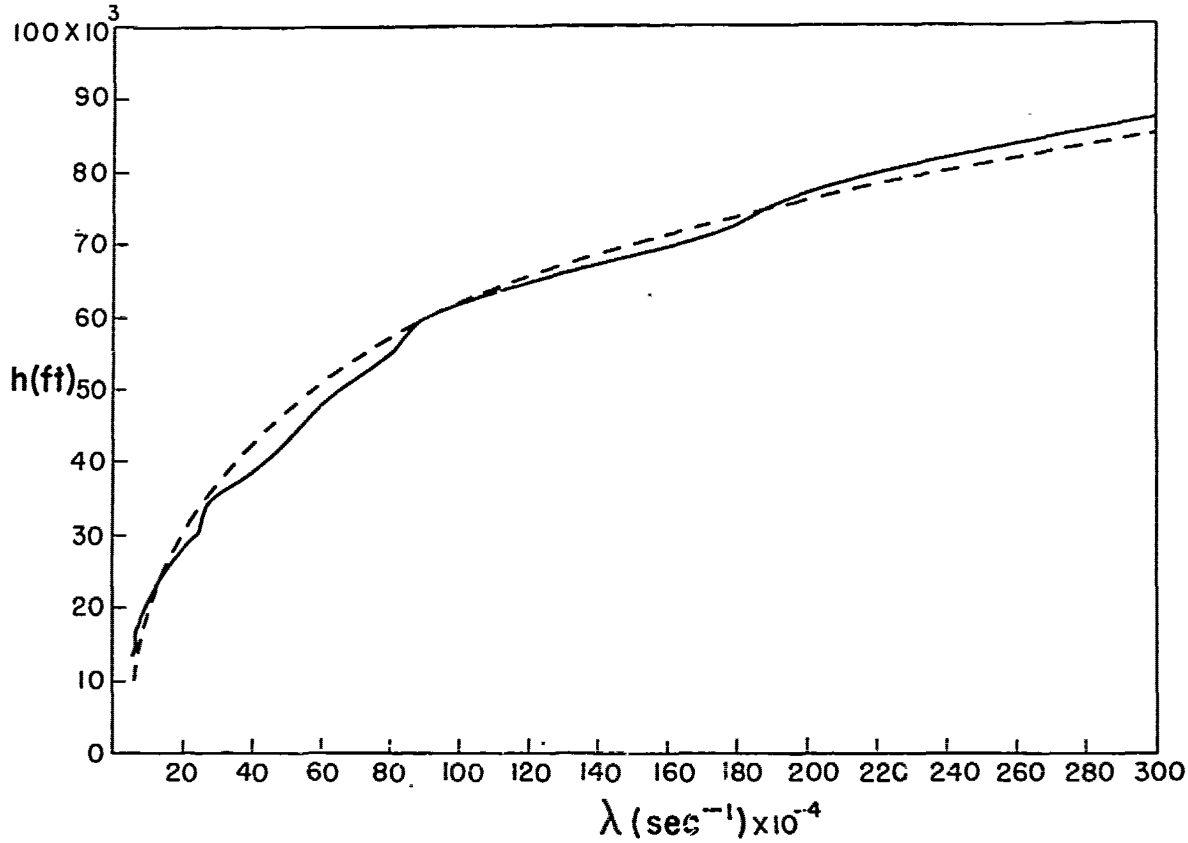


Fig. 4--Relationship of negative conductivity to altitude on descent, Flight 4 (dashed line represents theoretical curve)

altitudes. (3) The values of conductivity measured during descent show practically no fluctuation. (4) The descent data show that the value of conductivity increases monotonically with increasing altitude. There is no indication whatsoever of regions with abnormally low values of conductivity in the range of altitudes investigated.

<u>Theoretical calculations</u>--In this section we shall calculate the values of conductivity as a function of altitude to be expected from cosmic ray intensity data. The equation governing the time rate of change of atmospheric ions is given by

$$\frac{dn}{dt} = q - \alpha n^2 - \beta N n \quad (1)$$

where n represents the concentration of small positive or negative ions (ions/cc), q the rate of production of ions (ion pairs/cc sec), α the recombination coefficient between small ions, N the concentration of Aitken nuclei, charged and uncharged, and β the combination coefficient between nuclei and small ions. Thus, the αn^2 and $\beta N n$ terms represent the destruction of small ions due to combination with small ions and Aitken nuclei, respectively.

If ionic equilibrium exists and no nuclei are present in the region of the atmosphere under consideration, then

$$q = \alpha n^2 \quad (2)$$

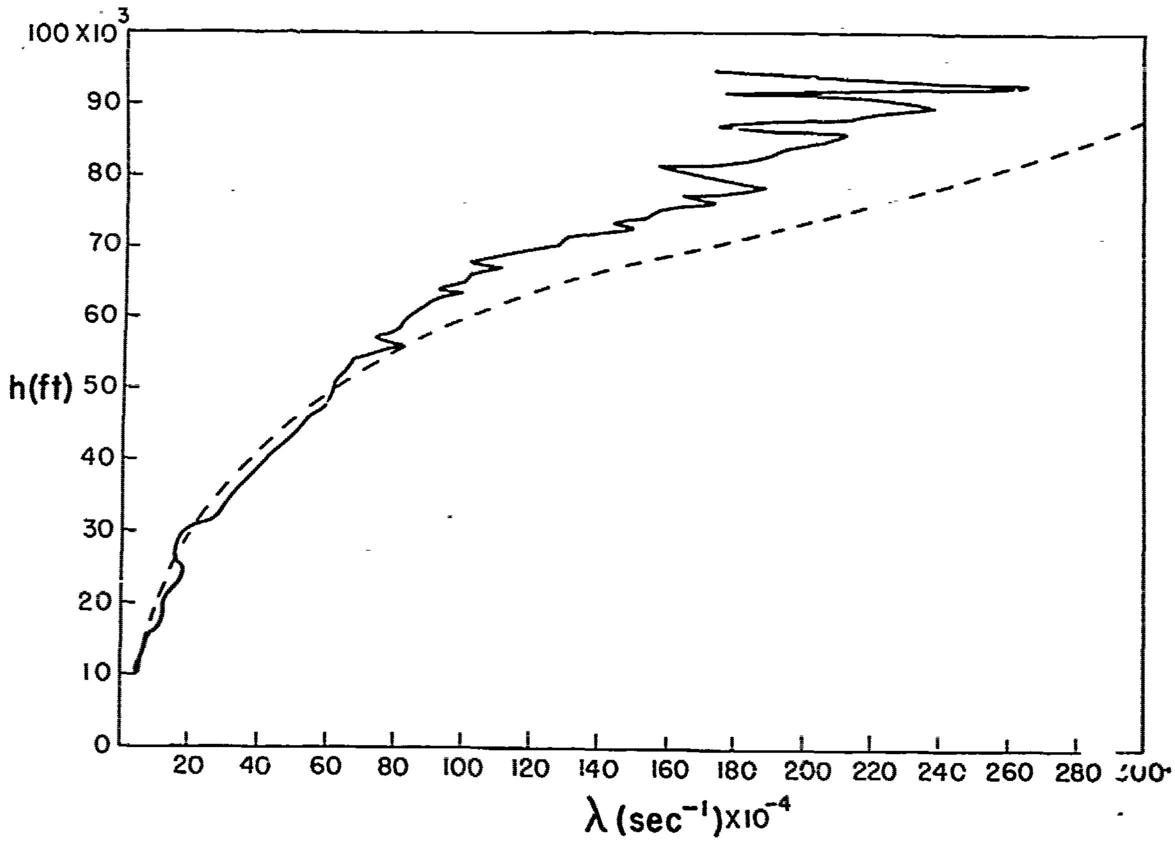


Fig. 5--Relationship of positive conductivity to altitude on ascent, Flight 5 (dashed line represents theoretical curve)

The conductivity of the atmosphere is given by

$$\lambda = n\,e\,k \qquad (3)$$

where λ represents the conductivity, e the unit electrical charge and k the mobility of the small ions. From these equations we immediately obtain

$$\lambda = e\,k\sqrt{q/\alpha} \qquad (4)$$

Thus, the conductivity of the atmosphere, assuming ionic equilibrium and the absence of nuclei, may be calculated from a knowledge of q, α, and k.

The rate of production of ions, q, was obtained from Millikan's cosmic ray intensity data [BOWEN, MILLIKAN, and NEHER, 1938] obtained at San Antonio, Texas, in 1938. Cosmic ray intensities at Texas in 1938 may not be the same as those at New Mexico in 1953, but nothing better was available. Millikan's data are expressed in terms of ion pairs/cc sec at a pressure of 76 cm Hg and 20°C. To reduce these to the values to be expected for our measured temperatures and pressures, we made use of the relation that the ionization intensity is directly proportional to the density of the gas.

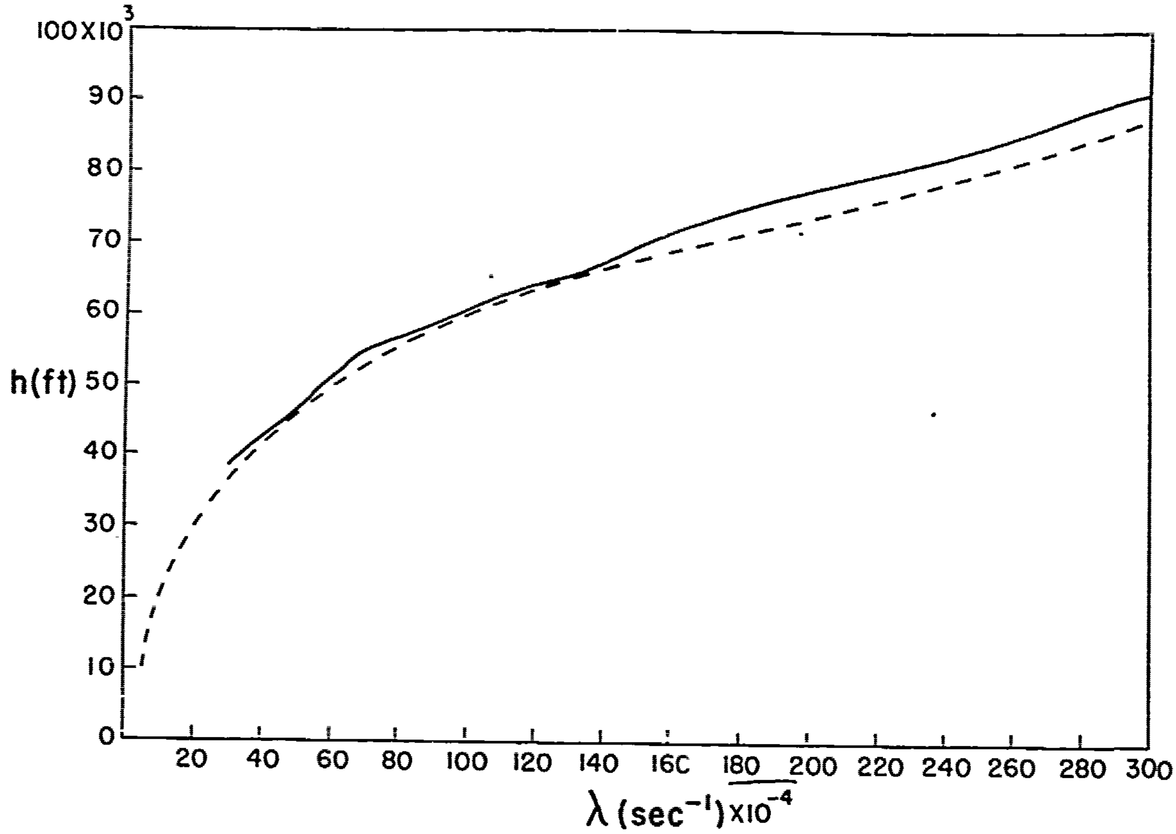


Fig. 6--Relationship of positive conductivity to altitude on descent, Flight 5
(dashed line represents theoretical curve)

The mobility, k, as a function of altitude was calculated using a value of 1.3 (cm/sec)/(volt/cm) as the mobility at 273°K and 76 cm Hg (this value having been measured by several investigators) and the relation that the mobility of the ions is inversely proportional to the density of the gas.

The recombination coefficient, α, was calculated using the Thomson theory of volume recombination [LOEB, 1939, p. 112]. According to this theory

$$\alpha = 1.75 \times 10^{-5} (273/T)^{3/2} (1/M)^{1/2} f(x) \quad (5)$$

where T represents the absolute temperature, M the molecular weight of the ions in question, and f(x) the probability that recombination will occur after the ions have approached to a certain critical distance where active attraction sets in. The probability function is given by

$$f(x) = 1 - (4/x^2) [1 - e^{-x} (x + 1)]^2 \quad (6)$$

where the independent variable, x, is

$$x = 0.81 (273/T)^2 (p/760) L_A/L \quad (7)$$

and where p represents the pressure in mm Hg, and L_A/L is the ratio of the mean free path of a molecule to that of an ion at normal temperature and pressure. The value of the ratio is approximately three for air.

The molecular weight of the ions is also unknown. This may be found by inserting a measured value of α in (5). The value of α at 20°C and 760 mm Hg has been reported by several investigators to be 1.6×10^{-6} cc/sec. Using this value in (5) we obtain

$$\alpha = 1.93 \times 10^{-6} (273/T)^{3/2} f(x) \ldots\ldots\ldots\ldots (8)$$

as the relation for the recombination coefficient which was used in these calculations.

Having determined q, k, and α as a function of altitude, the values of conductivity as a function of altitude were calculated by means of (4). The results of the calculations for Flights 4 and 5 are shown in Figures 3, 4, 5, and 6. These theoretical curves, we emphasize, are the curves to be expected if cosmic rays are the only source of ions and no Aitken nuclei are present in the atmosphere. Aitken nuclei, if present in sufficient concentration, would cause a diminution in the values of conductivity from those calculated.

Discussion of results--Examination of the experimental and theoretical ascent curves, Figures 3 and 5, shows that in the lower regions of the atmosphere the measured values of conductivity exhibit a moderate amount of fluctuation and follow the theoretical values approximately. In the higher regions of the atmosphere, however, the fluctuations in the measured values become very pronounced and the average value of the measured conductivity is definitely less than the theoretical value.

The descent curves, Figures 4 and 6, however, give an entirely different picture. In this case, not only do the measured values of conductivity follow very closely the theoretical values, but there is practically no fluctuation in the measured values throughout the entire region investigated.

The question immediately arises as to why there should be such a difference in the ascent and descent results. Are the fluctuations observed on the ascent indicative of conductivity fluctuations in the atmosphere or is the effect instrumental? We have no definitive answers to these questions but shall mention some probable causes for the results obtained.

First, from the fact that practically no fluctuations are present on the descent, we conclude that the ascent fluctuations are instrumental and not indicative of conductivity fluctuations in the atmosphere. One may argue that the instrument descended so fast that any conductivity fluctuations that may have been present in the atmosphere were automatically averaged out. However, when the rate of descent and the response of the instrument are taken into account it appears very unlikely that this is so.

As to the possible reasons why fluctuations are present on the ascent and not on the descent, we may cite the following. The electrostatic charge on the balloon may very well have affected the instrument on the ascent. This effect would, of course, be absent on the descent by parachute. That balloons charge up has been known for a long time, but the order of magnitude of this charge is completely unknown, as far as we are aware. We did try to minimize this effect by suspending the instrument several hundred feet below the balloon but interference from the balloon cannot be ruled out.

Another factor which varies between ascent and descent is the rate at which air flows through the conductivity chamber. In Figure 1 note that the descent rate is much greater than the ascent rate. What possible effect might this have on the conductivity readings? Figure 7 shows the current-voltage characteristics of a conductivity chamber of the type used on these flights. The curve OACD is the experimental curve obtained under laboratory-controlled conditions, whereas OABCD is the theoretical curve for this type of chamber. If the chamber is operated on the linear portion of the curve OB, then theoretically if the applied voltage across the chamber is less than V_2 the conductivity measured should be independent of the speed of the air through the chamber. Experimentally, however, we find that the applied voltage should be below V_1 in order to have the chamber operating on the linear portion of the curve. In the case shown in Figure 7, V_1 is about 26 pct lower

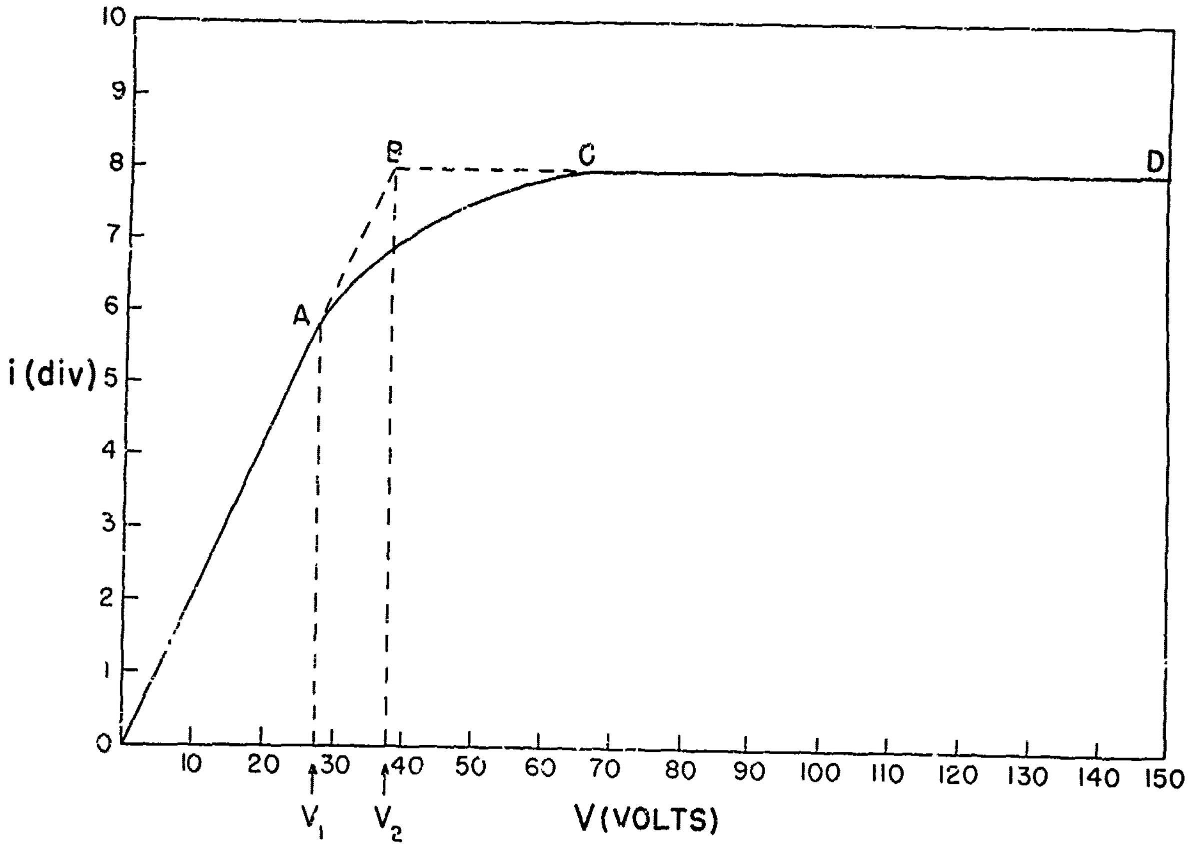


Fig. 7--Current-voltage characteristics of conductivity chamber

than V_2. Under other laboratory conditions, V_1 was found to be from 20 to 50 pct lower than V_2. Thus to be sure that the conductivity chamber is operating properly, the applied voltage should be at least 50 pct lower than the calculated voltage V_2.

On descent, where the air speed was relatively high, we feel certain that the chamber was operating on the linear portion of the characteristic curve where the conductivity measured is independent of the air speed. On the ascent, however, the operating voltage was not too much lower than V_2. Changes in air speed would therefore affect the measured values of conductivity. And the speed of the air through the chamber was far from constant. Observation of the balloon as it ascends indicates that its motion is quite irregular. Such conditions tend to make for fluctuations in the conductivity values. This possible explanation also fits the fact that the mean value of the measured conductivity is less than the calculated value, for a low value of air speed means a low apparent value of conductivity.

Thus the conductivity values obtained on the descent are much more reliable than those obtained on the ascent.

Conclusions--Assuming the descent data shown in Figures 4 and 6 to be reliable, we may make the following conclusions:

(1) The conductivity of the atmosphere increases monotonically with height from ground up to 100,000 ft above sea level.

(2) The measured values of conductivity agree very well with the calculated values based on cosmic ray intensity data.

(3) No diminution in conductivity at 65,000 ft above sea level as observed on the Explorer II flight was found. This means that during the periods of our flights no significant concentration of Aitken nuclei were present in this region of the stratosphere. This does not mean that nuclei are never present in the stratosphere. All we can say from our limited number of flights is that the presence of nuclei in the stratosphere is not a universal phenomenon.

Acknowledgments--We are grateful to the members of the balloon unit at Holloman Air Development Center, Alamogordo, New Mexico, for successfully launching the balloons used in this investigation.

References

BOWEN, I. S., R. A. MILLIKAN, and H. V. NEHR, New light on the nature and origin of incoming cosmic rays, Phys. Rev., v. 53, pp. 855-861, 1938.

CORONITI, S. C., and Others, Balloon borne conductivity, Instrumentation for Geophysical Research, no. 3, pp. 1-9, published by Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass., 1954.

GISH, O. H., and K. L. SHERMAN, The electrical conductivity of air to an altitude of 22 kilometers, Nat. Geogr. Soc., Stratosphere ser. 2, pp. 94-133, 1936.

HOLZER, R. E., and D. S. SAXON, Distribution of electrical conduction currents in the vicinity of thunderstorms, v. 57, no. 2, pp. 207-216, 1952.

LOEB, L. B., Fundamental processes of electrical discharges in gases, John Wiley and Sons, 717 pp., 1939.

McDONALD, J. E., On the electrical conductivity of the lower stratosphere, Trans. Amer. Geophys. Union, v. 34, pp. 529-533, 1953.

ROCKET PANEL, Pressures, densities, and temperatures in the upper atmosphere, Phys. Rev., v. 88, no. 5, pp. 1027-1032, 1952.

ON THE VARIATION OF ELECTRICAL CONDUCTIVITY OF AIR WITH ELEVATION

Gerhard F. Schilling

Institute of Geophysics
University of California, Los Angeles, California

Abstract--Measurements of the electrical conductivity of air have been made at both land and sea stations in California and in the Pacific Ocean. The observation sites were located in a variety of different climatic regions and ranged from shipboard locations to mountain tops exceeding 4000 m in elevation. The evaluation of the results shows a consistent increase of the mean value of positive conductivity with station elevations, essentially independent of location. A similar consistency is found for the altitude variation of the mean diurnal fluctuation which follows an exponential expression, decreasing with elevation. The comparison of the surface measurement results with free atmosphere data, obtained by other investigators during airplane and balloon flights, leads to unexpected agreement between mean absolute values at corresponding heights. It is not yet possible to present a complete explanation of the observation but possible effects of the variation of nuclei and radioactive substances present in the atmosphere are discussed.

Introduction--The present paper is one of a series of articles presenting results of the atmospheric-electrical research program of the Institute of Geophysics at the University of California. The principal objectives and the methods of approach are described in another paper [HOLZER, 1955]. In the course of the experimental investigations which included field measurements of the atmospheric electrical potential gradient, air conductivity, and the air-earth current density, observations of the electrical conductivity of air were made at stations ranging in elevation from sea level to 4030 m. These measurements are of interest in themselves and the topic of this presentation will be limited to a discussion of the results of such conductivity observations.

Instrumentation--The equipment used for measuring the atmospheric conductivity consists of a cylindrical air flow condenser system of the type first used by GERDIEN [1905] and a current measuring device. The ion current collected at the central electrode is passed through a resistance of 10^{11} ohm. The resulting potential drop is measured with a vibrating reed electrometer and recorded with an Esterline-Angus pen recorder with a one milliampere movement.

It is well known that one of the main problems of such measurements is the reliability of absolute values. The calibration method of SMITH [1953] was used and the system adjusted to record polar conductivities directly in reciprocal ohm-meters times 10^{-14} (esu $\times 10^{-4}$ = ohm^{-1}m^{-1} $\times 0.9 \times 10^{-14}$). The estimated accuracy of the absolute calibration is ten per cent. It is pertinent to mention that the equipment has been compared with apparatus used by CALLAHAN and Others [1951] for aircraft measurements and was found to agree within five per cent. Thus, the agreement with the instruments of Callahan is better than the estimated accuracy of the absolute calibration.

Observations--The principal information about the various measuring stations is given in Table 1. As can be seen, both land and shipboard sites, as well as island locations have been included. For purposes of comparison, a few additional stations where results have been obtained by other investigators [PARKINSON and WELLER, 1955; WAIT and TORRESON, 1948; WAIT, 1953; TORRESON and WAIT, 1948] are shown.

During an attempt to compare the local characteristics of the different stations which were situated in a variety of climatic regions, it became apparent that the mean values of positive conductivity showed a consistent increase with the elevation of the observation site. Figure 1 illustrates

Table 1--List of measurement sites

Designation	Elevation	Name	Coordinates	Period	Location
	m				
CRE	0	M/V Crest	112-120°W,25-30°N	1952	East Pacific Ocean
CHA	0	USCG Chautauqua	135°W, 33°N	1952	East Pacific Ocean
MIN	0	USCG Minnetonka	145°W, 29°N	1952	East Pacific Ocean
HOR	0	M/V Horizon	108-195°W,30°N-23°S	1952-53	Central Pacific Ocean
WLA	115	West Los Angeles	118°27'W,34°5'N	1951-54	Southern California
SLR	300	San Luis Rey	117°20'W,33°15'N	1953	Southern California
CAT	550	Catalina Island	118°25'W,33°25'N	1952	Coast Southern Calif.
SAG	750	Sage	116°55'W,33°35'N	1952	Southern California
LHS	900	Lake Henshaw	116°45'W,33°15'N	1953	Southern California
PMT	1730	Palomar Mountain	116°50'W,33°22'N	1952-54	Southern California
TMT	2290	Table Mountain	117°40'W,34°23'N	1953	Southern California
HAL	2900	Haleakala Mtn.	156°W,21°N	1953	Maui (Hawaii)
WM I	3350	White Mtn. I	118°W, 37°N	1952-53	Central California
WM II	3810	White Mtn. II	118°W, 37°N	1953	Central California
WM III	4030	White Mtn. III	118°Wm 37°N	1953	Central California
A	0	American Chief	2-75°W, 40-53°N	1952	Atlantic [PARKINSON and WELLER, 1953]
W	240	Watheroo	115°E, 32°S	1924-34	Australia [WAIT and TORRESON, 1948]
T	770	Tucson	110°51'W,32°15'N	1947-51	Arizona [WAIT, 1953]
H	3330	Huancayo	75°W, 12°S	1924-34	Peru [TORRESON and WAIT, 1948]

this relationship in quite a decisive manner. Note that the individual mean values are not strictly equivalent for this comparison, since the number of hourly samples for each station ranged from as little as 24 up to a few thousands for certain sites. In spite of this obvious disadvantage, a definite relation with elevation exists. It has been mentioned earlier that it is difficult to compare absolute values of conductivity obtained by various authors, because of the calibration problems involved. Nevertheless the few values entered where comparable equipment has been used, show a general agreement with our altitude relation.

The result that the mean variation of positive conductivity with elevation seems to be a consistent phenomenon, is not too surprising, although such a relation could have been expected *a priori* only under the assumption of more or less similar local conditions (with reference to nuclei content and rate of ion production, as well as their time variations) at the various measurement sites. Obviously one would not have made such an *a priori* assumption in the light of much evidence to the contrary at low level surface stations.

However, in Figure 1 the mean values of conductivity obtained by CALLAHAN and Others [1951] in the free atmosphere, and the computed relation by GISH and WAIT [1950], based on airplane and Explorer II data, have been entered too. The rather good agreement between these free atmosphere data and our surface values could not have been anticipated and is indeed more difficult to explain than any disagreement.

Before discussing this phenomenon, we wish to examine Figure 2, where the altitude variation of F, the fluctuation of positive conductivity, is shown. The fluctuation has been defined as the difference between the maximum and minimum values of the mean diurnal variation, divided by the diurnal mean. Again we find a relation with station elevation, but a number of stations seems to deviate appreciably. Referring to Table 1 it can be seen that these particular stations have local characteristics quite different from a conventional surface station; they are ocean and island sites.

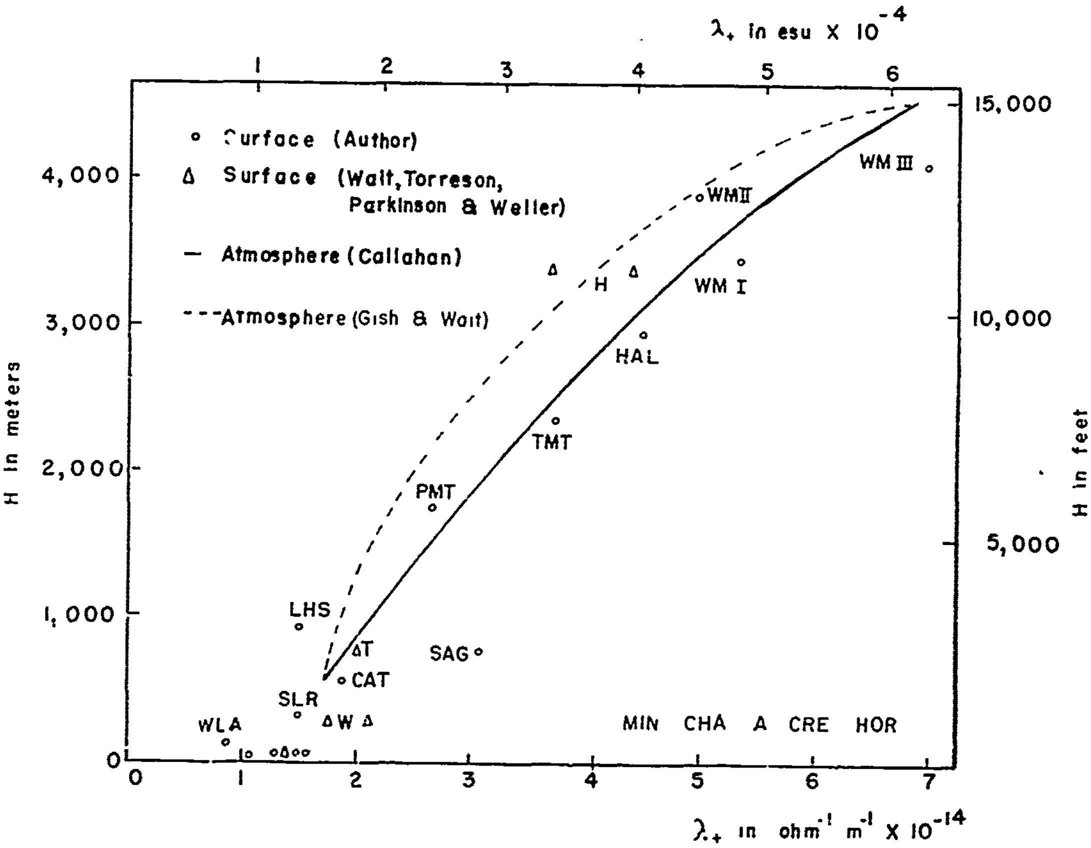


Fig. 1--Variation of positive conductivity of air with altitude above sea level

Figure 2 shows that the majority of the stations follow a relationship which can best be approximated by an empirical exponential function of the type

$$F = Fo + Ae^{-h/H}$$

where Fo is the abscissa value of the asymptote, arbitrarily taken as corresponding to the mean fluctuation found over oceans, A has the value of 0.85, and H is 2400 meters. If it can be assumed that this decrease of the fluctuation with elevation is principally due to the decrease of nuclei content with altitude, the height of 2400 m might very well correspond to the approximate average height of the top of the exchange layer, as discussed by SAGALYN and FAUCHER [1955].

Discussion--In general it can then be stated that the investigation has yielded three experimental results of significance.

(1) The increase of positive conductivity with elevation for surface stations shows a definite consistency rather independent of location.

(2) Not only the rate of this increase, but also the absolute mean values at higher elevations seem to be close to the corresponding values in the free atmosphere.

(3) The diurnal fluctuation of conductivity measured near the surface decreases with elevation in a nearly exponential manner.

In discussing these results it is necessary to emphasize that they apply to mean values and therefore mean conditions of the electrical conductivity of air near the Earth's surface. This refers

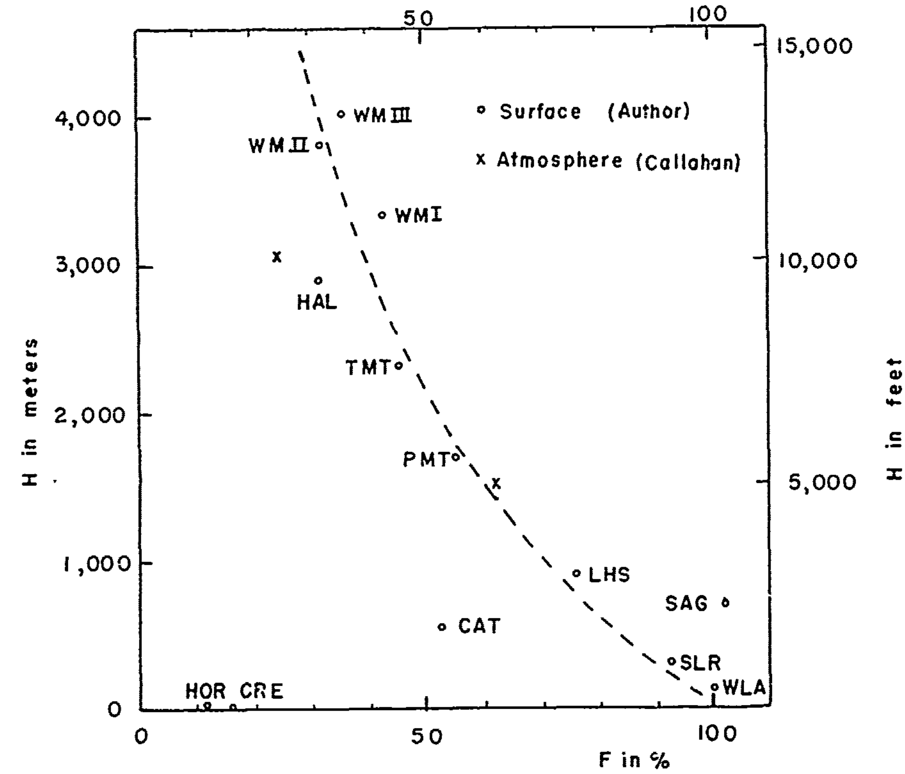


Fig. 2--Altitude variation of the fluctuation of positive conductivity of air

also to the mean fluctuation of the distinct diurnal variation well known to occur at all land stations according to local time. Some additional information with regard to ocean measurements on this point is presented by RUTTENBERG [1955].

When we look for the cause of this apparent consistency in the conducting properties of the atmosphere, we are in effect investigating the variations of two variables in time and space, that is, the rate of production of ions and the amount of nuclei present. The former we can further divide into an ion production rate due to cosmic rays and one due to radioactive substances in and near the surface of the Earth. We also know that the cosmic ray ionization increases with altitude. but remains essentially constant in time at a given height; whereas, the nuclei content should decrease with elevation and have random as well as regular time variations superimposed. As a preliminary assumption we might take the ionization due to radioactive substances as being independent of elevation, but we certainly must consider it as a function of time. We can also neglect an increase of small ion mobilities with decreasing air densities but only when comparing surface and free atmosphere data inter se.

If we concentrate for the moment on a given altitude within the exchange layer, it is difficult to see even with these simplifying assumptions why the mean value of conductivity found at a land station at this elevation should be rather independent of local characteristics. Considering that we are accustomed to account for typical local influences at measurement sites as due to varying nuclei content, particle concentrations, and space charges, we would expect much larger deviations from one station to the next.

In addition, we note that the rate of vertical increase of the mean surface value of positive conductivity at the higher elevations is comparable to the rate of increase in the free atmosphere.

Even the absolute values at a given altitude seem to be comparable, the surface conductivities being at the most only slightly higher than in the free atmosphere. Which means that in spite of the distinct diurnal variation at surface stations, that is, high night and low daytime values, the daily mean values are practically identical with those measured by airplanes and balloons at corresponding heights above the ground. Since airplane measurements seem to indicate the presence of a dividing line between the exchange region with high nuclei content and the undisturbed atmosphere with stable electrical conductivities above, the values of conductivity at higher altitudes in the free atmosphere are generally considered as being due primarily, if not exclusively to cosmic ray ionization. This concept now does not seem to hold for the exchange region.

Conclusions--It has not been possible to develop a complete explanation of the observations on the basis of existing data. The additional experimental data vitally needed for the development of an adequate theory are: (1) observations of the mean diurnal variation of the conductivity in the free atmosphere at various altitudes both over land and sea surfaces (in particular, present data need to be supplemented with nighttime observations), and (2) observations of the ionization rates in the free atmosphere, particularly in the exchange layer.

In the absence of such data one can draw only speculative conclusions. The results on the variation of conductivity with elevation suggest that the austausch process transports upward not only nucleii, but also radioactive substances in appreciable quantity. The ion-production rate of the radioactive material in the atmosphere may play a role as significant as the nucleii concentration in fair weather observations of conductivity. The selective absorption of radioactive emanation by aerosol particles was, indeed, suggested by ISRAEL [1934] as early as 1934. Recent studies by COTTON [1955] and certain aspects of the investigation of DAMON and KURODA [1954] also point to the possible importance of the introduction of radioactive materials into the free atmosphere. Further study of the influence of radioactive materials introduced into the austausch layer from the surface promises to yield important information for atmospheric electrical studies at the surface of the Earth.

Acknowledgments--Credit must be given to a number of individuals who participated in the comprehensive task of performing the measurements, especially G. Bundy, R. Dickinson, N. Hamilton, K. Lee, L. G. Smith, and L. Tepley. The laboratory and field work was under the supervision of S. Ruttenberg and the office work under H. Pitkin. The research reported in this paper was made possible through support and sponsorship extended by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract No. AF19(122)-254.

References

CALLAHAN, R. C., S. C. CORONITI, A. J. PARZIALE, and R. PATTEN, Electrical conductivity of air in the troposphere, J. Geophys. Res., v. 56, pp. 545-551, 1951.

COTTON, E. S., Diurnal variations in atmospheric radioactivity, Proc. Conference on Atmospheric Electricity, May 1954, Air Force Camb. Res. Center, pp. 67-77, 1955.

DAMON, P. E., and P. K. KURODA, On the natural radioactivity of rainfall, Trans. Amer. Geophys. Union, v. 35, pp. 208-216, 1954.

GERDIEN, H., Demonstration eines Apparates zur absoluten Messung der elektrischer Leitfaehigkeit der Luft, Physik. Zs., v. 6, pp. 800-801, 1905.

GISH, O. H., and G. R. WAIT, Thunderstorms and the Earth's general electrification, J. Geophys. Res., v. 55, pp. 473-484, December, 1950.

HOLZER, R. E., A program of simultaneous measurement of air-earth current density, Proc. Conference on Atmospheric Electricity, May 1954, Air Force Camb. Res. Center, pp. 96-100, 1955.

ISRAEL, H., Emanation und aerosol, Beitr. Geophys., v. 42, pp. 385-408, 1934.

PARKINSON, W. D., and R. I. WELLER, Atmospheric electric elements over the ocean, J. Geophys. Res., v. 58, pp. 270-272, 1953.

RUTTENBERG, S., and R. E. HOLZER, Atmospheric electrical measurements in the Pacific Ocean, Proc. Conference on Atmospheric Electricity, May 1954, Air Force Camb. Res. Center, pp. 101-108, 1955.

SAGALYN, R. C., and G. F. FAUCHER, Aircraft investigations of the large-ion content and conductivity of the atmosphere, Proc. Conference on Atmospheric Electricity, May 1954, Air Force Camb. Res. Center, pp. 27-42, 1955.

SMITH, L. G., On the calibration of conductivity meters, Rev. Sci. Instr., v. 24, no. 10, p. 998, October, 1953.

TORRESON, O. W., and G. R. WAIT, Atmospheric-electric results at Huancayo Observatory, Peru, 1924-1934, Washington, D. C., Carnegie Inst. Pub. 175, v. 19, 1948.

WAIT, G. R., Investigation of electrical properties of the atmosphere, Washington, D. C., Carnegie Inst., Appendix Final Rep. Contract AF19(604)-251, 1953.

WAIT, G. R., and O. W. TORRESON, Atmospheric-electric results at Watheroo Observatory, Western Australia, 1924-1934, Washington, D. C., Carnegie Inst. Pub. 175, v. 17, 1948.

ATMOSPHERIC ELECTRICITY ASSOCIATED WITH JET STREAMS

Vincent J. Schaefer

The Munitalp Foundation, Inc.
Schermerhorn Road
Schenectady, New York

Abstract--A simple and inexpensive method is described for studying the atmospheric electricity which often occurs in direct relation to the major axis of a jet stream. The equipment consists of an easily erected telescopic aluminum mast bearing a radioactive gold probe. The mast is insulated from the ground and connected by a shielded cable to a sensitive micro-ammeter. Positive current flow to the ground in the range of 0.04-0.12 microamps is commonly observed under a jet stream when using a 35 ft mast. Observations such as have been made by Falconer and the writer at the G. E. Research Laboratory have recently been extended in an effort to better understand the complex relationships which occur. During the past year a few measurements were made on the summit of Gisborne Mountain in northern Idaho. In eastern New York in active study of this phenomenon is now underway as part of the basic research program in atmospheric physics of the Munitalp Foundation.

During the winter of 1944 at the summit of Mt. Washington, New Hampshire, a study of atmospheric electricity was started in an effort to learn something about the physical nature of precipitation static. A number of interesting results were obtained at the Observatory on the mountain and subsequently at low level observation points in eastern New York. The results of these studies have been described in a series of papers and reports [LANGMUIR, 1945; SCHAEFER, 1947, SCHAEFER, LANGMUIR and Others, 1946].

Since that time certain phases of the Mt. Washington studies have been continued, especially in the field of supercooled clouds, ice-crystal nuclei, and atmospheric electricity. With the discovery of the dry ice effect [SCHAEFER, 1946] and related developments in experimental meteorology [SCHAEFER, 1953a], an intensive program of continuous meteorological observations was inaugurated at the General Electric Research Laboratory. These have been described [FALCONER, 1949].

Early in our study of electrical effects in the atmosphere we encountered a number of anomalous phenomena. These were unlike the so-called 'cross current' storms in which the sign of the current flow from the collecting probe to ground changes from positive to negative with respect to ground potential every 20 or 30 minutes and which have been correlated with snow, rain, and thunderstorms, and the passage of warm and cold fronts. The effects were more like the so-called 'positive current' storms during which the sign of the current flow from collecting probe to ground had a positive sign with respect to ground potential with occasional peaks reaching values of + 0.25μA. These occurred during snow storms consisting of ice crystals falling from cirrus cloud levels in the sky.

The unusual effects observed in this early work occurred during fair weather, often when the sky was completely cloudless and the atmosphere brilliantly clear with unlimited visibility.

At other times, it occurred in conjunction with fast moving high and middle clouds. One case was noted in which the winds at 10,000 ft were measured at 54 knots. The amount of electrical current did not exceed 0.1 microamp and, in some cases, was barely detectable with the ordinary metal point collector then in operation. Several interesting effects were observed which were termed 'ghost storms'. Evidence was cited [SCHAEFER, 1947] to show that these were related to the pas-

sage of relatively large space charges associated with evaporated crystals from snow showers. By locating two stations about 2.5 miles apart, it was possible to show that such space charges moved with the velocity of the air at cloud level. Measurement of atmospheric electricity during this early period was made by using four types of collectors, including two sizes of cylinders, an ellipsoid, and a sharp point. Subsequent studies were made exclusively with the point collector. Although the electrical effects observed with this simple device are closely related to the potential gradient of the atmosphere, this term is not used in this paper since the effects observed may vary somewhat from the values of the potential gradient measured by more conventional instruments. Until a better understanding of the observed effects has been obtained, the electrical effects measured will be referred to as 'probe to earth currents.' A positive current represents the condition in which the probe exposed to the sky is more positive than the Earth's below, that is, electrons flow from Earth to probe and thence to the atmosphere. Conversely a current flow having negative sign represents the conditions in which electrons flow from the atmosphere to the probe and thence to earth.

During the latter phases of Project Cirrus, a government sponsored research program in experimental meteorology, it was decided to increase the sensitivity of the point discharge collector. This was done by having the brass needle point wrapped with gold foil impregnated with a radium salt. About 1.6 cm^2 of gold foil was used which contained radium equivalent to 250 micrograms. The results of these latter observations have been described by FALCONER [1949].

These data present strong evidence that the fair weather anomalies consisting of unusual amounts of atmospheric electricity are related to the 'ghost storms' previously described but to an even more specialized degree.

Studies of jet stream clouds--At about the same time that precipitation static studies were started at the General Electric Research Laboratory early in 1944, the writer observed on several occasions spectacular sequences of fast moving, high altitude cirrus clouds. The unusual feature noted in these early observations was the remarkably coherent pattern of the clouds, which appeared as cirrus cloud streets, their high velocity, and the unusual directions from which they appeared. The case which first drew attention to the phenomenon was a stream of high level air flowing from the northeast. In 1947 the writer first heard of jet streams during a paper presented by C.G.Rossby. Rossby's description of jet streams fitted into the pattern of observations which had been made by the writer, but it was not until five years later that the opportunity arose to follow up this study. With the issuance of 500 and 200 mb isotach charts by WBAN on the weather map Times Fascimile network, a means became available to conduct a correlation of observable cloud systems and the presence of the major axis of a jet stream.

Within a few months, it became obvious that a high correlation existed between certain distinctive cloud formations and the presence of the major axis of a jet stream. It was found that four basic cloud types may form in a jet stream and that they generally have certain physical characteristics. These have been described in two illustrated papers [SCHAEFER, 1953 bc].

Shortly after the writer pointed out the apparent relationship of distinctive cloud patterns often formed within jet streams, FALCONER, [1953] found that a number of the anomalies of unusual amounts of fair weather atmospheric electricity could be closely related to the presence overhead of the major axis of a jet stream. He found that during the five-month period of October 1952 to February 1953 on 80 pct of all days with highest atmospheric electrical activity the band of jet stream winds was directly over the observation area in eastern New York.

Since initiating the observation of atmospheric electricity at Schenectady in 1944, the records have been obtained over extended periods with a continuously recording microammeter. (General Electric Photoelectric Recorder, Schenectady, New York. 0.5 micro-amp full scale.) Using a chart speed of two inches an hour the more recent records are detailed enough to show fine structure variations in current flow without producing excessive amounts of record

Electrical currents related to atmospheric effects--The past ten years of observations with the point collector have produced records which may be roughly divided into three general patterns. Two of these fit into the pattern which has been observed by other investigators; the third, which we believe is related in some manner to the presence of a jet stream, has not been studied in detail.

Fair-weather electrical effects are characterized by a flow of current having a positive sign from probe to Earth in the range of + 0.0005 to + 0.01 microamps using our method. This may occur with cloudless skies, fair-weather cumulus, stratus overcasts, and slow moving altocumulus and cirrus clouds. Figure 1 shows a typical record.

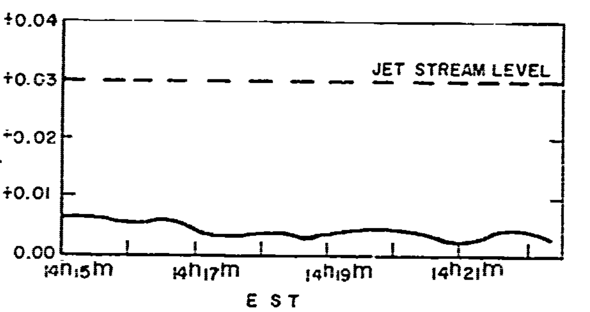


Fig. 1--Typical probe-to-Earth current associated with fair-weather electrical effects, July 7, 1954

What may be termed Storm electrical effects are typified by considerable variations in current and sign of current flow. The outstanding feature is the alternation in sign of the current flow. These alternations in sign of the current often occur at ten to thirty minute intervals and show a high correlation with snowfall, rainfall, lightning discharges, the passage of large convective cloud cells, the movement of warm and cold frontal systems, and similar visible meteorological phenomena. Values are generally in excess of 0.1μA and may exceed 5.0μA with the sign both positive and negative with respect to ground potential. Figure 2 illustrates a typical section of such a record.

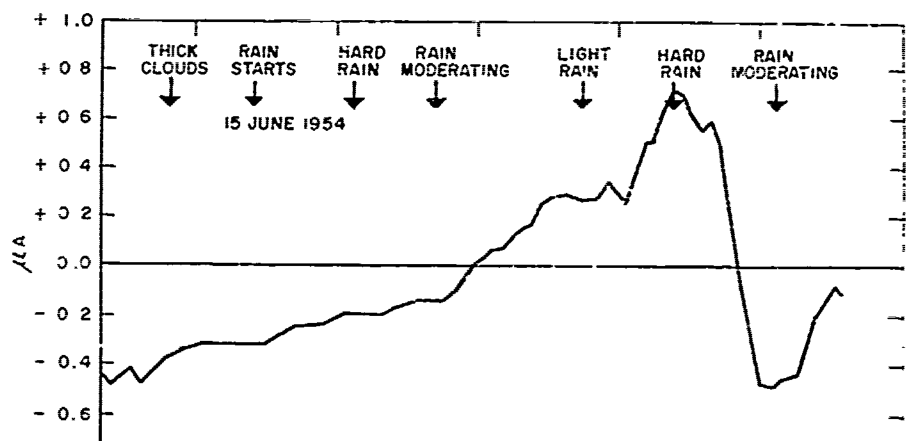
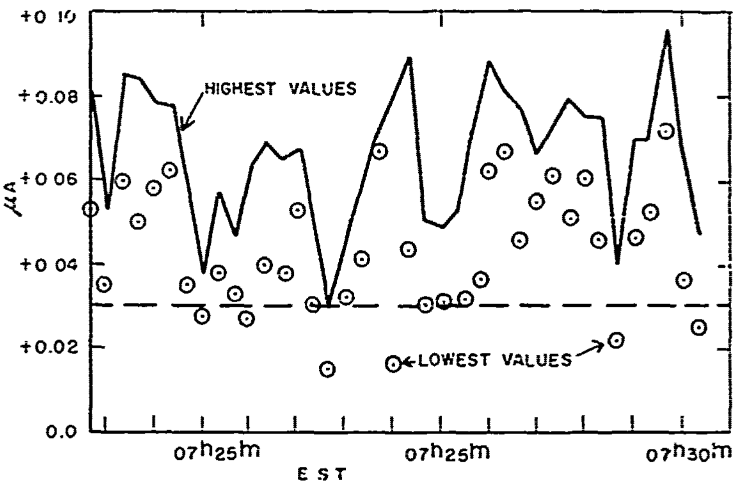


Fig. 2--Typical probe to Earth current of both positive and negative sign associated with storm electrical effects, June 15, 1954

Between the values of the positive sign fair weather electrical effects and the positive and negative sign storm electrical effects but having unmistakably unique characteristics is a third general pattern of atmospheric electricity which we propose to term jet stream electrical effects. The sign of the probe to Earth current flow is positive, and its range is between 0.015 and 0.10μA.

The lower limit of the amount of current depends to a considerable degree on the type of exposure given the radioactive probe to the sky and certain other features which will be described but are not at present well understood. Figure 3 shows typical records.



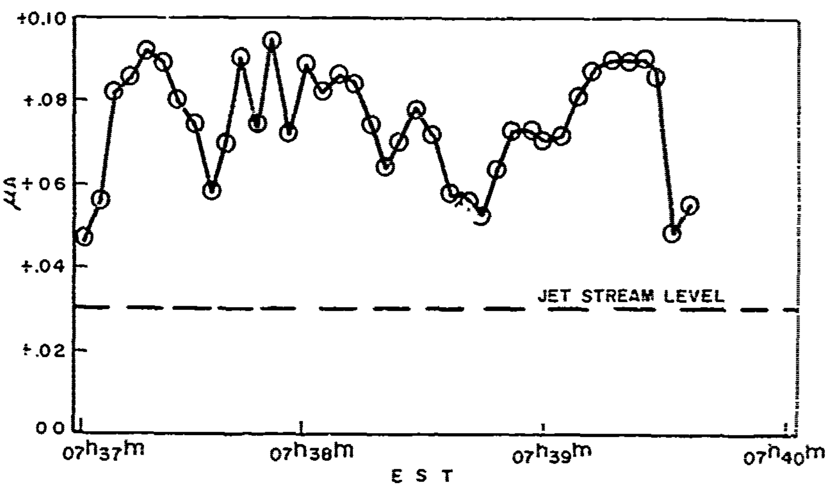


Fig. 3--Typical probe-to-Earth current of positive sign associated with jet stream electrical effects; upper curve is example of 20-second maximum and minimum values while lower curve shows a four-second interval sequence

Method of measuring jet stream electrical effects--There are a number of methods which may be used for detecting the atmospheric electrical effects which seem to be closely associated with the presence overhead of high velocity winds. Although the evidence accumulated thus far presents strong evidence that most of these high values are closely associated with the near proximity of the core of a jet stream, there are features of the observations which are difficult to interpret in the light of our present knowledge. These will be mentioned later. The main features of the observational method have been described in the papers and reports by Schaefer and Falconer previously mentioned.

The apparatus is very simple. It consists of a brass needle point wrapped with a small strip of radioactive gold. This needle is soldered into a bushing which is connected by shielded cable through a sensitive microammeter to ground. The sensing element must be well insulated to avoid leakage currents. This is not difficult, however, since the double insulator which we have described [SCHAEFER, 1947], and which is simple to construct, provides excellent insulation even during heavy rain storms.

An even simpler arrangement has recently been devised for studying jet stream electrical effects. This consists of a 36-foot telescopic aluminum mast (No. AL 535 made by Premax Prod. Div., Chisholm-Ryder Company, Inc., Niagara Falls, N. Y.) mounted on a base insulator and supported with insulated wires. The top length of the antenna pole is of 5/16-inch diameter aluminum rod, the upper end of which is threaded to hold the radioactive probe. In this manner, the aluminum pole serves as a conductor with a shielded cable connecting its base to the high side of the grounded microammeter.

A simple and very satisfactory method has been devised for mounting this telescopic pole for temporary field use. A cylinder of dry wood or other non-conductor four inches long and having a diameter equal to the outside dimension of the lowest section of the pole is fashioned so the top edge fits loosely into the lower end of the pole. A three-eighths inch hole, two inches deep, is bored into the bottom of this plug. Several layers of polyethylene or a similar insulating sheeting eight inches in diameter are then placed so that they separate the plug from the metal pole. When assembled, the sheeting projects beyond the shoulder of the plug as a skirt and serves as a rain barrier. A brass or copper rod 3/8 inch in diameter and four to five feet long is then driven into the ground until one foot remains above it. This serves the dual purpose of a ground connection, as well as a rest for the plug at the bottom of the pole. Three stakes are driven into the ground six feet from the ground rod and 120° apart. Insulated guy ropes fastened on a ring above the first section of the telescopic pole support it rigidly and complete the installation. With this arrangement a 36-foot pole may be erected by one person in less than five minutes.

While it is desirable if possible to use a recording microammeter, the lack of one does not preclude making interesting and useful records.

A simple, relatively inexpensive, and reliable microammeter is the RCA type WV 84 ultrasensitive D. C. microammeter. This reads full scale for 0.01 microamp at its most sensitive setting and may be easily read to $0.0001 \mu A$ or 1×10^{-10} amp. Such low values are rarely encountered in atmospheric electricity with the unit as described. This instrument is particularly convenient since fair weather electrical effects occur with the 0.01 × scale setting, jet stream electrical effects on the 0.1 × scale, and storm electrical effects on the 1.0 × scale. This unit may also be used as a nearly drift-free amplifier for driving a less sensitive recorder.

<u>Procedure for obtaining manual records of electrical effects</u>--Since it is observed that most atmospheric electrical effects of importance to meteorological phenomena persist over periods of an hour or more, occasional manual observations have considerable scientific value. Such short observations are no substitute, however, for a continuous automatic recorder if suitable instruments are available.

Satisfactory short-period records may be obtained in the following manner. A hand operated or electrically driven timer having an interval in the range of ten to 30 seconds is used. During the fixed time interval, the needle of the microammeter is watched and the high and low values noted and plotted directly on graph paper. A period of five to ten minutes has been found to be sufficient to get a fairly good representation of the tendencies which occur on typical days of the three types of effects mentioned.

An even simpler procedure has been found to be fairly representative of the tendencies over shorter time intervals. This method consists of plotting instantaneous values at a regular but unhurried rate. With limited practice it has been found that such values may be noted and plotted at

inter ls of four seconds for a period of five to ten minutes. Figure 3 illustrates the two methods. While these methods tend to ve tedious and have definite limitations of usefulness, the methods are still of considerable value for exploratory field studies. This is especially true where limited facilities would prevent any research in this important field.

The effect of wind--The most perplexing aspect of the high values of fair weather current seemingly associated with jet streams as measured with the radioactive probe is the effect of calm and light winds on current flow. This problem is rarely encountered if the radioactive probe is located on a high building, a mountain top, or other promontory where air movements generally exceed 1.5 to 3.0 m/sec, even during so-called calm periods. With the air surrounding the radioactive probe moving slower than 1.5 m/sec, the current flow even with the core of a high velocity jet stream overhead may show an average reading of less than 0.015 microamp. Under such conditions, a sudden gust of wind will often cause the current flow to temporarily increase to a value of 0.04 to 0.07 microamp. That this condition is not related to the wind alone is indicated by the observation that during periods in which the major axis of a jet stream is absent, winds of much greater velocity fail to show values higher than 0.01 microamp. It is as though there were a tendency for a local space charge to build up in quiet air which produces a net negative charge surrounding the radioactive point. This tends to nullify the positive current 'jet-stream effect.' It is only when the air movement is sufficient to 'blow away' this local effect that the higher values may 'come through.' It may be that variations of this effect are responsible for the diurnal variations which have been observed by other workers using the more conventional instruments for measuring potential gradients and air-earth currents. Such effects have been described as background 'noise.' It is obvious that much more research is needed to understand these anomalies.

A period of observations on the summit of Gisborne Mountain in northern Idaho during August, 1953, showed us that even on a high mountain summit in regions where winds frequently die down during the night, a strong diurnal decrease in current flow during the night period is of common occurrence. More recently similar studies have been inaugurated at the Mt. Washington Observatory in New Hampshire where our original work in atmospherics started ten years ago. These studies will be directed toward achieving an understanding of the effects of wind, cloud, jet streams, and related phenomena at a high, precipitous, windy mountain summit using a radioactive probe connected to a recording microammeter.

Low values of atmospheric electricity related to radioactive fallout--For the three weeks following May 1, 1953, and for about two weeks in April 1954, the level of atmospheric electricity in eastern New York dropped to a very low level of activity even during the presence of the major axis of a jet stream. This lack of activity was even more difficult to understand when several active convective rain storms failed to produce cross-current effects. The 1953 period was subsequently found to coincide with a fallout of radioactive debris from atomic explosions which had been conducted in Nevada. Subsequent studies indicated that although the level of radioactivity did not present a health hazard it was sufficient to reduce the level of atmospheric electricity to very low values. Fortunately, the radioactive dust had a short half life so that by June 1, 1953 the probe to Earth currents were again showing normal variations.

A similar though less pronounced effect occurred starting April 14, 1954, following a rain shower which left a light deposit of radioactive mud in eastern New York. Gathering a small sample of the mud on a piece of moist filter paper and placing it near a Geiger-Muller counter, the normal counting rate was increased three to four times above that of the ordinary background level caused by cosmic rays and related phenomena. The source of the radioactive mud is not known at the present time, although it occurred shortly after the nuclear tests in the Pacific area. As in the previous year, the return to the more normal variations of atmospheric electricity occurred several weeks afterward.

The cause of jet stream electrical effects--Several theories have been suggested by Falconer to explain the atmospheric electricity which seems to be associated with the presence of jet streams.

He reasons that since these high-velocity air flows are often intimately associated with stormy areas such as thunderstorms and tornadoes, the net positive charge commonly observed in the upper part of such storms would often be carried away in the jet-stream winds and thus have a space charge effect many miles from the original storm. This is a similar effect to the ghost storms I previously mentioned.

Falconer also suggests that the Simpson-Scrase [CHALMERS, 1949] ice-friction theory might add to these effects since it is now well known that the sky is rarely free of high-level ice crystals. The high shear and turbulence often occurring in the jet stream would tend to intensify such effects.

The recent discovery of REYNOLDS [1954] that variations in temperature of ice particles is sufficient to cause charge separation of large magnitude when the particles make momentary contact should also be considered. Time lapse motion pictures of jet-stream clouds present strong evidence that rapid changes occur in clouds which form in jet streams. Large temperature differences, turbulence, shear, drag, and instability of air containing solid and liquid particles combine to produce ideal conditions for such effects to occur. Since some of the highest values of jet-stream electrical effects accompany air movements with trajectories from the polar regions during the winter time, I am inclined to favor the latter mechanism for the development of an elongated space-charge-level region along the major axis of a jet stream.

Since it is often observed that jet stream electrical effects occur under conditions which would not favor the movement of the charges to the collector site, it is likely that many of the observed effects may be caused by induction with the turbulent motions of the stream of ionized particles producing the current flow observed.

This effect may be simulated by waving a small charged sheet of polyethylene in the general vicinity of the radioactive point. Such a sheet two feet square moved at the rate of a meter a second at a distance of 50 ft will produce a momentary increase in current flow of 0.02 microamps. Whether this induction effect is a satisfactory answer must await further research studies.

The actual delivery of positive charges to the collector cannot be dismissed on the basis of our present evidence. The fact that the highest values are intimately associated with localized air movement when the major axis of the jet stream is in the immediate vicinity raises the alternate possibility that the space charge effects produced or carried by a jet stream must reach the collector to cause the observed effects.

One of the meteorological phenomena I have found to be closely associated with the major axis of a jet stream is a zone of gusty winds at ground level. These occur mostly when the lapse rate is high. It is under such conditions that space charges might be transported from higher levels toward the ground. A study of variations in ozone content of the lower air in regions free of air pollution might shed light on this transport mechanism since it might be expected that the ozone concentration would also be high under a jet stream if air from high altitude reaches the ground.

The formation of liquid-water clouds above the station is nearly always accompanied by a decrease in value of the positive air to Earth current. It has been observed many times that with a jet stream overhead containing cirrus clouds and causing probe to Earth currents of the order of 0.04 to 0.07 microamps the formation of a small strato-cumulus cloud directly above the station at an altitude of 5000-8000 ft will produce a dip in the current flow to a value of 0.015 to 0.025. Whether this effect is due to shielding or to the actual development of a localized negative space charge is an interesting question.

<u>The need for studying jet stream electrical effects with a network of stations</u>--If it can be proved that what I have termed jet stream electrical effects are actually related to these high velocity streams of air, a widespread network of observing stations should be established for continuously monitoring such locations. A preliminary attempt in this direction is ready to operate. Recording stations are

established as a cooperative project at Buffalo, Syracuse, and Schenectady in New York; Mt. Washington in New Hampshire; Boston and Foxboro in Massachusetts, and at a location in New Jersey. With such a network it should be possible to establish the sensitivity of the method for locating a jet stream, since excellent examples are of common occurrence in the northeastern United States. A much smaller tripartite network with base lines of about 800 ft is in use by the writer for a study of local effects.

The main purpose of this paper is to direct attention to this interesting phenomenon and to point out the possibility of studying it with inexpensive equipment. Studies should be made in other regions of the world to discover whether the effects are widespread or only of a relatively local nature. Important new discoveries are likely to follow.

Acknowledgments--Until recently the observations made by the writer were made in cooperation with Raymond Falconer at the General Electric Research Laboratory, under their sponsorship as well as that of the U. S. Army, Navy, and Air Force who sponsored contracts of which the atmospheric electrical studies were a small part. At the present time, the writer's work is being conducted as part of the basic research program in atmospheric physics of The Munitalp Foundation.

References

CHALMERS, J. A., Atmospheric electricity, Oxford Univ. Press, pp. 159-160, 1949.

FALCONER, R. E., Some correlations between variations in the atmospheric potential gradient at Schenectady and certain meteorological phenomena, G. E. Res. Lab. Rep. RL 287, Schenectady, N. Y., 1949.

FALCONER, R. E., A correlation between atmospheric electrical activity and the jet stream, Final Rep., ONR Project, G. E. Res. Lab. Rep. RL 1007, Schenectady, N. Y., 1953.

LANGMUIR, I., Final report on investigation of fundamental phenomena of precipitation static, War Dept. Contract W-33-106-sc-65, May, 1945.

REYNOLDS, S. E., Thunderstorm charge structure and suggested electrification mechanisms, Proc. Conference on Atmospheric Electricity, May 1954. Air Force Camb. Res. Center, pp. 162-168, 1955.

SCHAEFER, V. J., The production of Ice crystals in a cloud of supercooled water droplets, Science, v. 104, pp. 457-460, 1946.

SCHAEFER, V. J., Properties of particles of snow and the electrical effects they produce in storms, Trans. Amer. Geophys. Union, v. 28, pp. 587-614, 1947.

SCHAEFER, V. J., Part I, Laboratory, Field, and flight experiments, Project Cirrus Final Report, G. E. Res. Lab. Rep. RL 785, Schenectady, N. Y., 1953a.

SCHAEFER, V. J., Clouds of the jet stream, Tellus, v. 5, pp. 27-35, 1953b.

SCHAEFER, V. J., The use of clouds for locating the jet stream, The Aeroplane, London; October, 1953c.

SCHAEFER, V. J., I. LANGMUIR, and Others, Basic icing research by General Electric Company, Fiscal Year 1946, AAF Tech. Rep. 5539, 1946.

DIURNAL VARIATIONS IN ATMOSPHERIC RADIOACTIVITY

E. S. Cotton

Geophysics Research Directorate, Air Force Cambridge Research Center
Air Research Development Command, Cambridge, Massachusetts

Abstract--Continuous measurements of the ionization produced inside two chambers operated at Bedford, Mass., during the autumn months of 1952 and 1953 are discussed, and comparisons are made with meteorological data at ground level. One of these chambers was constructed by the late G. R. Wait and has a cellophane wall of 1.6 mg/cm^2 absorption thickness. The second chamber uses a screen-wall and an outside clearing field to eliminate residual ions. The chambers and their modes of operation are described. Significant cases of meteorological influence are shown, and the order of magnitude of the diurnal changes is verified using diffusion concepts.

Experimental arrangement--The diurnal variations in atmospheric radioactivity have been investigated at many locations throughout the world since the first observations in the early part of this century [BECKER, 1934; BLIFFORD, LOCKHART, and ROSENSTOCK, 1952; CULLEN, 1946; HOGG, 1935; MACEK and ILLING, 1935; PRIEBSCH, RADINGER, and DYMEK, 1937; WAIT, 1946; WILKENING, 1952]. The general characteristics of such variations have been shown to have significant correlations with meteorological conditions, varying from point to point according to local atmospheric circulation and surface composition. It is the purpose of the present paper to describe diurnal effects under selected meteorological conditions at a particular site, and to relate these effects to turbulent exchange in the surface layer of the atmosphere.

The experimental equipment consisted of two ionization chambers of cylindrical shape. The first was constructed of wire mesh supported at the ends by wooden disks and covered by cellophane of 1.6 mg/cm^2 thickness. The collecting electrode was a brass rod of 3.2 mm diameter; the chamber was 21.8 cm in diameter and 36.5 cm in length. (This chamber was used by the late G. R. Wait at the Carnegie Institution for several of his experiments on atmospheric sources of ionization.) Insulators of amber and teflon were used during different periods. This will be referred to as the cellophane-wall or thin-wall chamber.

The second chamber, more complex in construction, consisted of an interior wire mesh cylinder 20 cm in diameter and 60 cm long supported on lucite disks, which were also covered with wire mesh. This screen was composed of 0.12-cm wire, 0.5-cm mesh and served as the high voltage electrode. On its axis, supported by a teflon insulator, was a 0.95-cm diameter collecting electrode of copper tubing. The entire chamber was surrounded by a second cylinder of wire mesh, 2.86 cm from the inside cylinder, and supported by aluminum disks on either end. The lower disk was the base plate and guard ring. The entire outer assembly was maintained at the potential of the electrometer case.

The field which exists between the outer grounded screen and the inner high voltage screen is sufficient to collect and effectively remove most of the atmospheric ions which would disturb the chamber. It does this quite well in a still atmosphere, but air currents through the chamber are disturbing and have been avoided in the continuous measurements. This chamber will be referred to as the screen-wall chamber.

Each chamber was mounted on the preamplifier unit of a Model 30 Applied Physics Corporation vibrating-reed electrometer, and resistors appropriate to the measured current were attached so that the electrometer effectively measured the voltage developed across the resistor. The voltage from each chamber was recorded on an Esterline Angus milliameter with a chart speed of 3/4 inch per hour. One hour time marks were produced by interrupting the current at hourly intervals.

The background contribution of the screen-wall chamber was found to be quite high when it was first assembled. It became necessary to silver-plate all the exposed metal parts in order to reduce this background to a reasonable value.

The investigations to be discussed were carried out at three locations in the vicinity of Hanscom Air Force Base in Bedford and Lexington, Massachusetts. During the autumn of 1952, the cellophane-wall chamber was operated continuously in a truck which was parked on the air base in a wooded area. The elevation of this site was 140 ft above sea level. Air was continuously exchanged between the truck and the outside by means of an air conditioner fan.

During the summer of 1953, the truck was taken to the top of a hill about one mile from the 1952 site, at an elevation of 306 ft. This hill is the highest point in the area. Both the cellophane-wall and the screen-wall chambers were operated at this site.

In September, 1953, after it was found that diurnal effects on the hill were extremely small, the truck was moved back into the valley to a site only 1300 ft from the 1952 location, at an elevation of 125 ft. The remainder of the data was taken here with both chambers operating continuously.

In all of these measurements the emphasis was on the diurnal variations of the current in the chambers rather than the absolute value of the rate of ionization per unit volume. However, we can take the average minimum values of current in the chambers to be representative of the so-called 'normal' rate of ionization. For these values we obtained 9.4 I for the cellophane-wall chamber and 12.7 I for the screen wall chamber, where I denotes the number of ion pairs produced per cubic centimeter per second. If we assume for the moment that background contributions due to chamber contamination are negligible, then using the data of HESS and VANCOUR [1951] the screen-wall chamber has a minimum contribution due to alpha emitters of 7.1 I, and the cellophane-wall chamber, a contribution due to alphas of about 3.9 I. The ratio of the contribution in the thin wall chamber to that in the screen-wall chamber would be thus about 0.55. However, taking into consideration the facts that the thin-wall chamber can be sensitive only to alpha particles which originate outside the

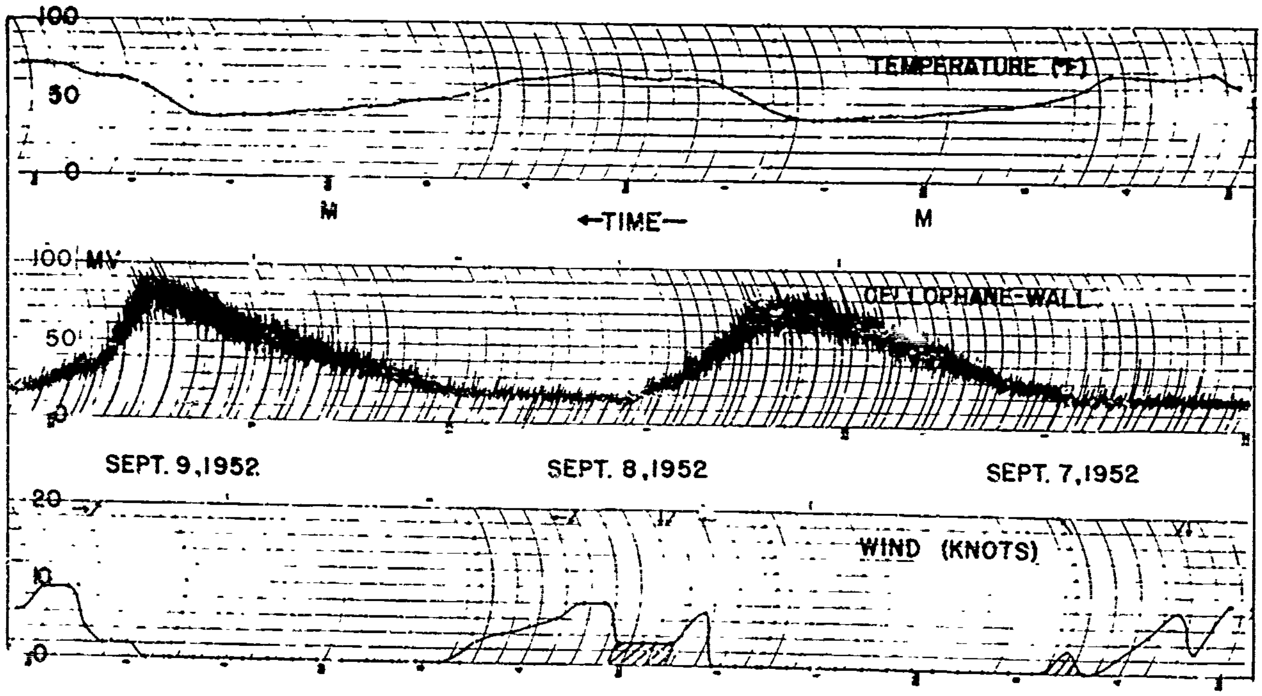


Fig. 1--September 7-9, 1953; full scale ionization = 47 I

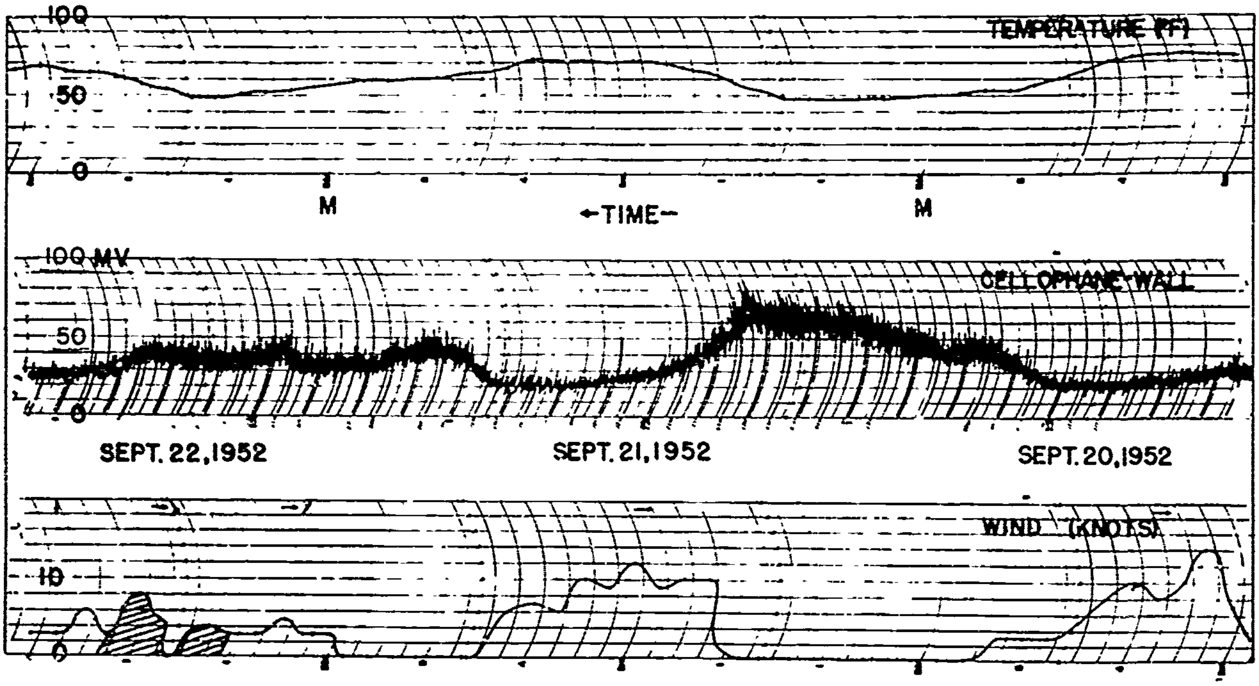


Fig. 2--September 20-22, 1952; full scale ionization = 47 I

chamber exclusive of contamination, and that the screen-wall chamber is sensitive to alpha particles originating both within and outside of the chamber, it has been calculated that the ratio of the alpha particle contributions within the thin-wall chamber to that within the screen-wall chamber should be about 0.15. From this it can be estimated that the contamination contribution is about 3 I in both chambers. The observed value of the ratio of current changes averaged over all the diurnal variations studied is 0.12, which is not in disagreement with the calculated value, 0.15.

Data--Those days on which significant diurnal effects were observed were selected from the periods of measurements and displayed with simultaneous records of surface temperature and wind velocity obtained from the Hanscom Air Force Base weather station. The meteorological variables were not measured continuously but were observed at least once an hour. In all cases except one, where pronounced nocturnal increases in ionization were observed, the wind speed was less than one knot. In order to gain a qualitative understanding of the variations and their relations to one another, several of these cases are presented. They are arranged in chronological order.

In the 1952 series (Fig. 1-5) the upper record shows the variation of temperature, the middle record, the ionization rate, and the lower record the wind speed. The cross-hatched areas on the wind record indicate changing wind direction. The arrows fly with the wind; the directions are the usual map directions. Time increases from right to left in all cases. Each figure represents a forty-eight-hour period of observation.

September 7-9, 1952 (see Fig. 1), the full scale reading on the ionization record corresponds to a 100 mv (instead of 1 mv) drop across the resistor connected to the central electrode in the ionization chamber. Full scale readings correspond to an ionization current of 10.3×10^{-14} amperes or an ionization rate of 47 I. One can see from this illustration the general nature of the diurnal curves. A single large maximum is observed in the morning at about 07h, as observed in many other places. The rapidity of the decrease from this maximum, and the onset of wind after the nocturnal calm are characteristic of surface temperature inversions and their subsequent dissolution.

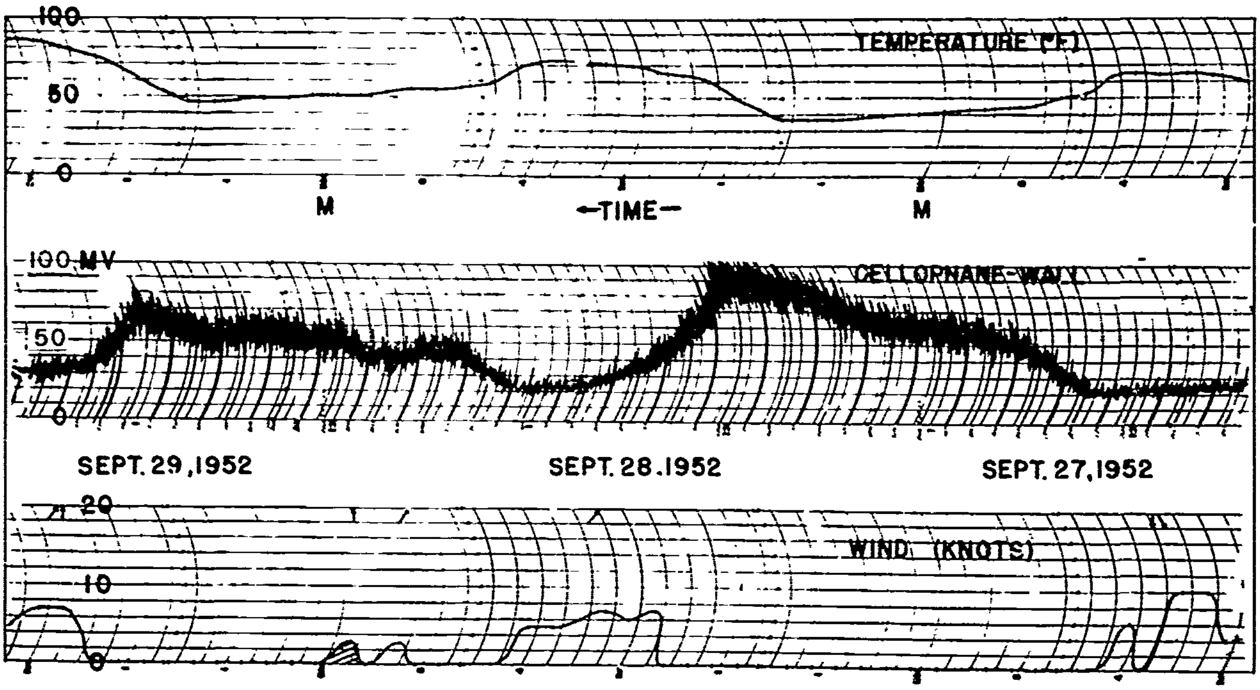


Fig. 3--September 27-29, 1952; full scale ionization = 47 I

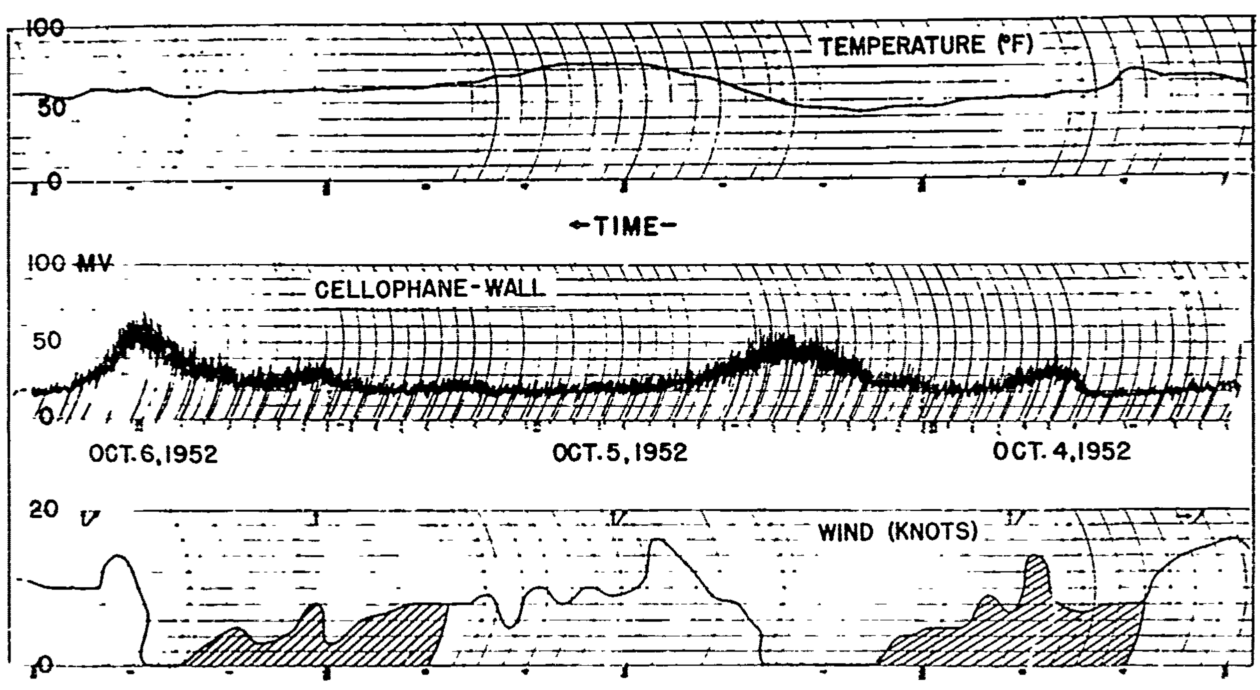


Fig. 4--October 4-6, 1952; full scale ionization = 47 I

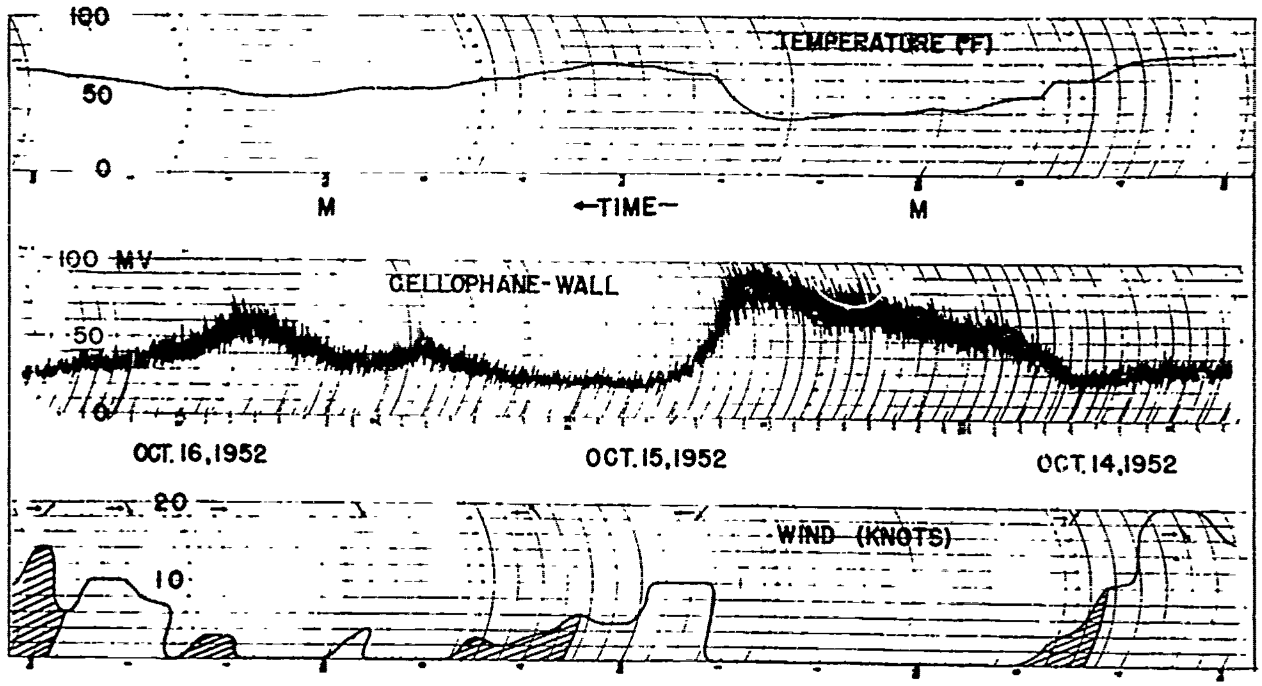


Fig. 5--October 14-16, 1952; full scale ionization = 47 I

Both of the variations shown here occurred with calm periods throughout the growth of the maximum. No secondary maxima are seen. Fine weather associated with a high pressure area dominated the period. Ground fog was present from midnight until 06h 30m during the morning of September 9.

The data for September 20-22, 1952 (Fig. 2), show the retarding effect of even a slight circulation on the development of an ionization maximum. Although meteorological conditions are approximately the same during these two nights, the development of the second maximum is cut off by a slight wind. Ionization values remain higher than normal, however, since the temperature inversion alone can restrict the upward exchange of radioactive emanation.

The data for September 27-29, 1952 (Fig. 3), show the same condition even more markedly. A small amount of horizontal circulation near midnight is sufficient to lower the eventual maximum in ionization. The secondary maxima seen here and in other figures are evidently associated with deviations from the increasing stability of the inversion.

The data for October 4-6, 1952 (Fig. 4), show how rapidly a small maximum can develop. In a period of four hours, the ionization increased from 11.8 I to 21.6 I, or a total of 9.8 I. In terms of radon emanation this amounts to about 10^{-15} curies per cubic centimeter. The next increase was even more rapid, although it appears to have begun before the wind ceased. The cessation of wind apparently acts somewhat like the closing off of a certain volume within which the emanation may accumulate; the height of the volume is determined by the lapse rate. For a more complete study of these phenomena, a measurement of the lapse rate in the lowest 1000 ft or so of the atmosphere would be necessary, particularly in the first 100 ft above the ionization apparatus.

The data for October 14-16, 1952 (Fig. 5), again show that the slight increase in circulation just before midnight retarded, and in fact reduced the ionization, so that a secondary maximum is seen. This effect is usually accompanied by a change in slope of the temperature curve, although

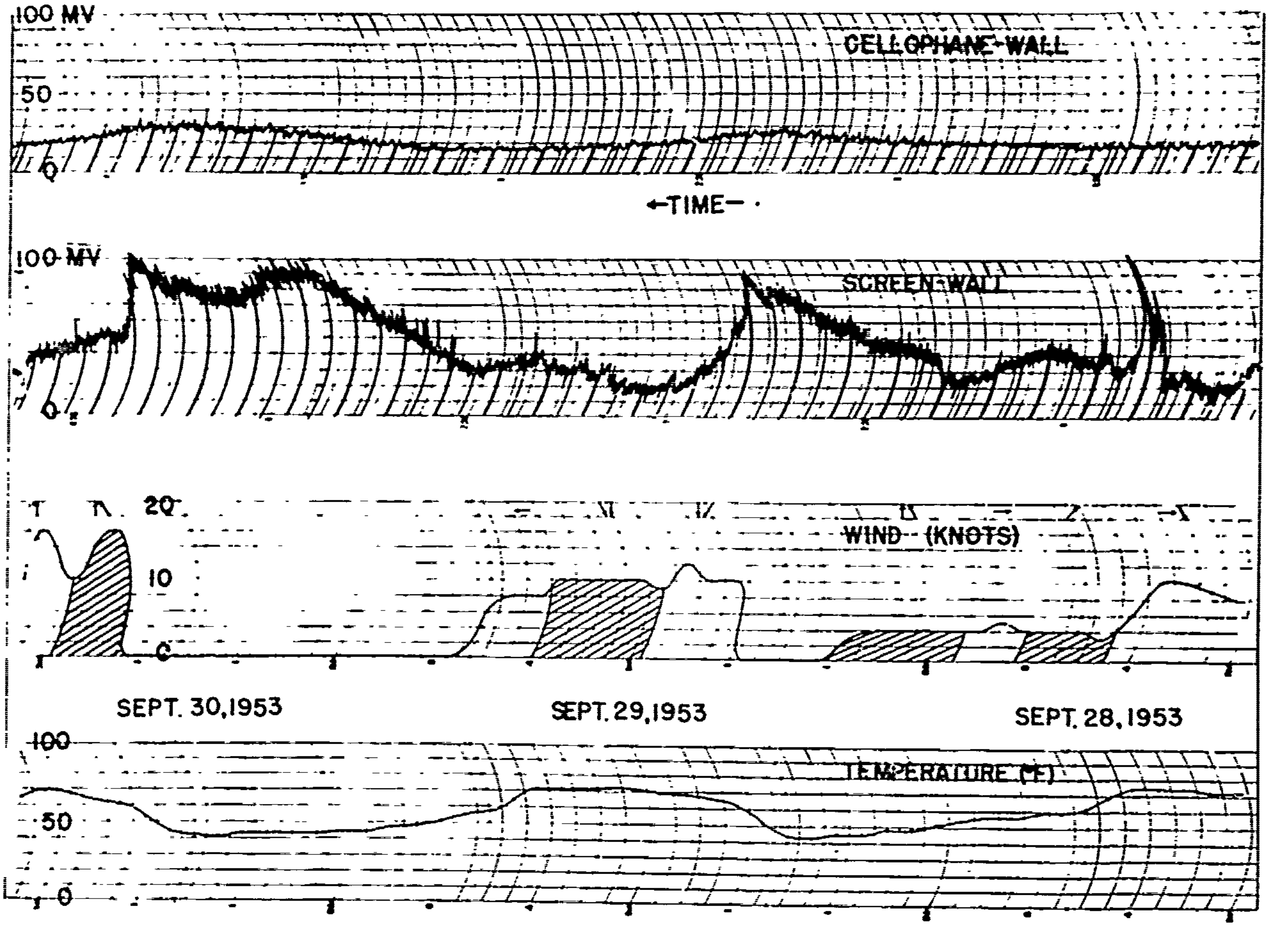


Fig. 6--September 28-30, 1953; full scale screen-wall ionization = 72 I;
full scale cellophane-wall ionization = 46 I

very slight. The rapid decrease in ionization on the morning of October 15 seems to be due to the sudden onset of wind. This relation is not quantitative.

In the 1953 series (Fig. 6-9), the cellophane-wall record is at the top, the screen-wall record is second from the top, the wind record is third from the top, and the temperature record is at the bottom.

The data for September 28-30, 1953 (Fig. 6), show the simultaneous operation of the two ionization chambers. The scale for both ionization records should read 1×10^3 mv, or one volt Full scale for the cellophane-wall chamber corresponds to 10.1×10^{-14} amperes, or 46 ion pairs/cm^3/sec. Full scale for the screen-wall chamber corresponds to 21.8×10^{-14} amperes, or 72 ion pairs/cm^3/sec.

It is evident that the screen-wall chamber has a larger ratio of diurnal variations to 'normal' readings, over the same period, than the cellophane-wall chamber. This justifies the use of the chamber, the design and construction of which were aimed at an increasing alpha ionization sensitivity. It is also evident that the screen-wall chamber is subject to fluctuations to which the cellophane-wall chamber does not respond. Some of these are felt to be real variations in radioactive

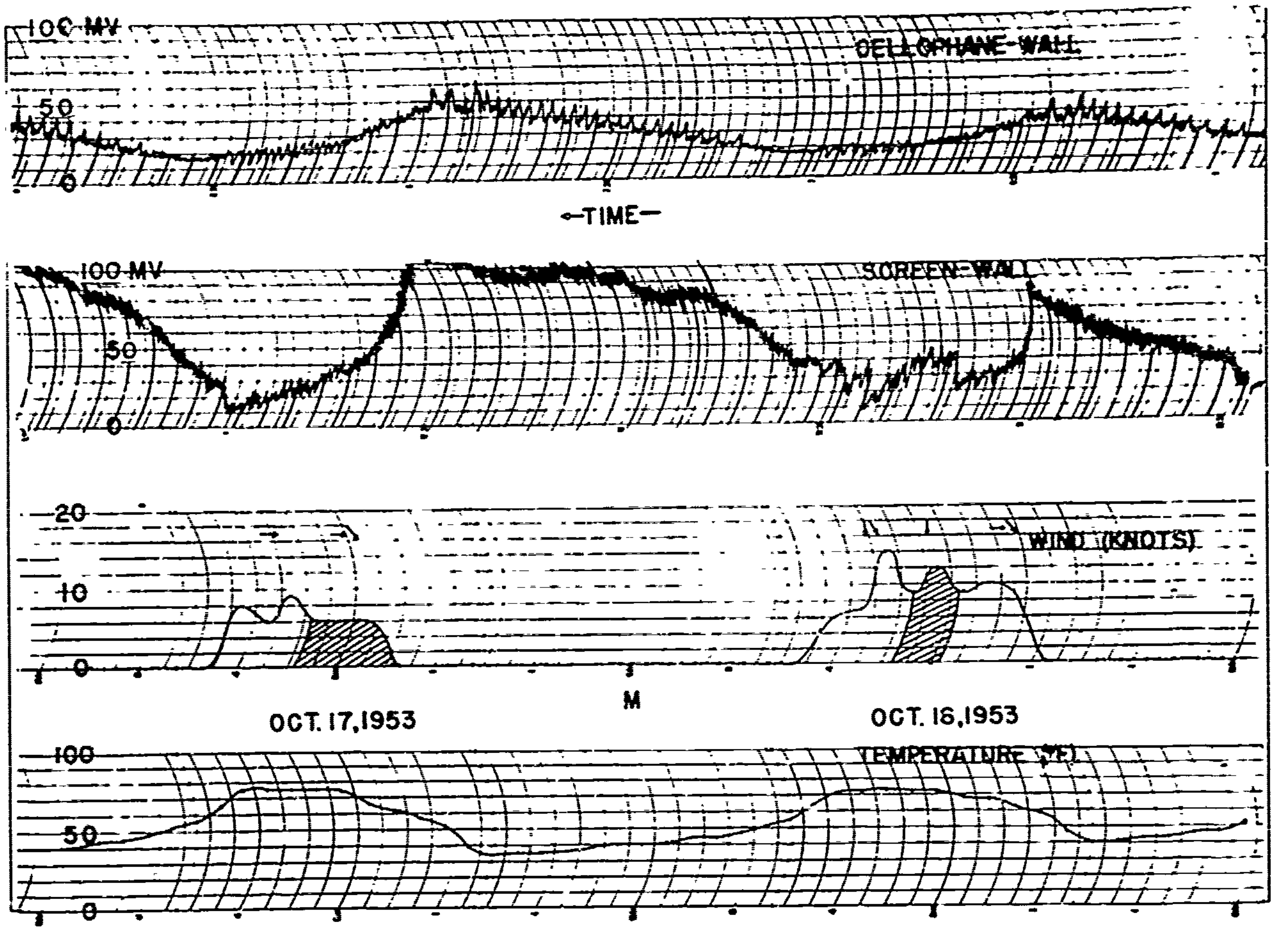


Fig. 7--October 16-17, 1953; full scale screen-wall ionization = 72 I, full scale cellophane-wall ionization = 46 I

content but others result from atmospheric ions which are forced through the screening field by air currents. Normally, however, the chamber was operating in a relatively quiet atmosphere, and its readings are at least indicative of relative changes in radioactive content. This chamber approximates the infinitely thin wall chamber which we desire for measuring ion production in the atmosphere; its sensitive volume is not biased in regard to the type of ionizing particles producing the ionization relative to the ionization in the free atmosphere. In this figure, the sudden increase on September 28 seems to be linked to a wind-speed decrease and pressure minimum. The fast decreases from maximum readings on September 29-30 seem to result from the rapid onset of wind on both days. The secondary maximum on September 30 occurs during a steady temperature trend. Ground fog was present during most of the period of build-up of the maximum (22h 28m-08h 58m).

The curves for the data of October 16-17, 1953 (Fig. 7) all show their characteristic periodicities. The diurnal effects are quite large on the chambers, although by no means as large as some observed in 1952, when the cellophane-wall chamber often went off scale. This may be caused by differences in soil exhalation, or to the fact that the 1952 area was wooded. However, it is noteworthy that the topographical gradient was much steeper at the 1952 site, although the elevation was nearly the same. Operation for two summer months in 1953 on the highest hill in the area gave almost no diurnal variations, so that the formation of stable layers in the valley at night seems to be the dominant

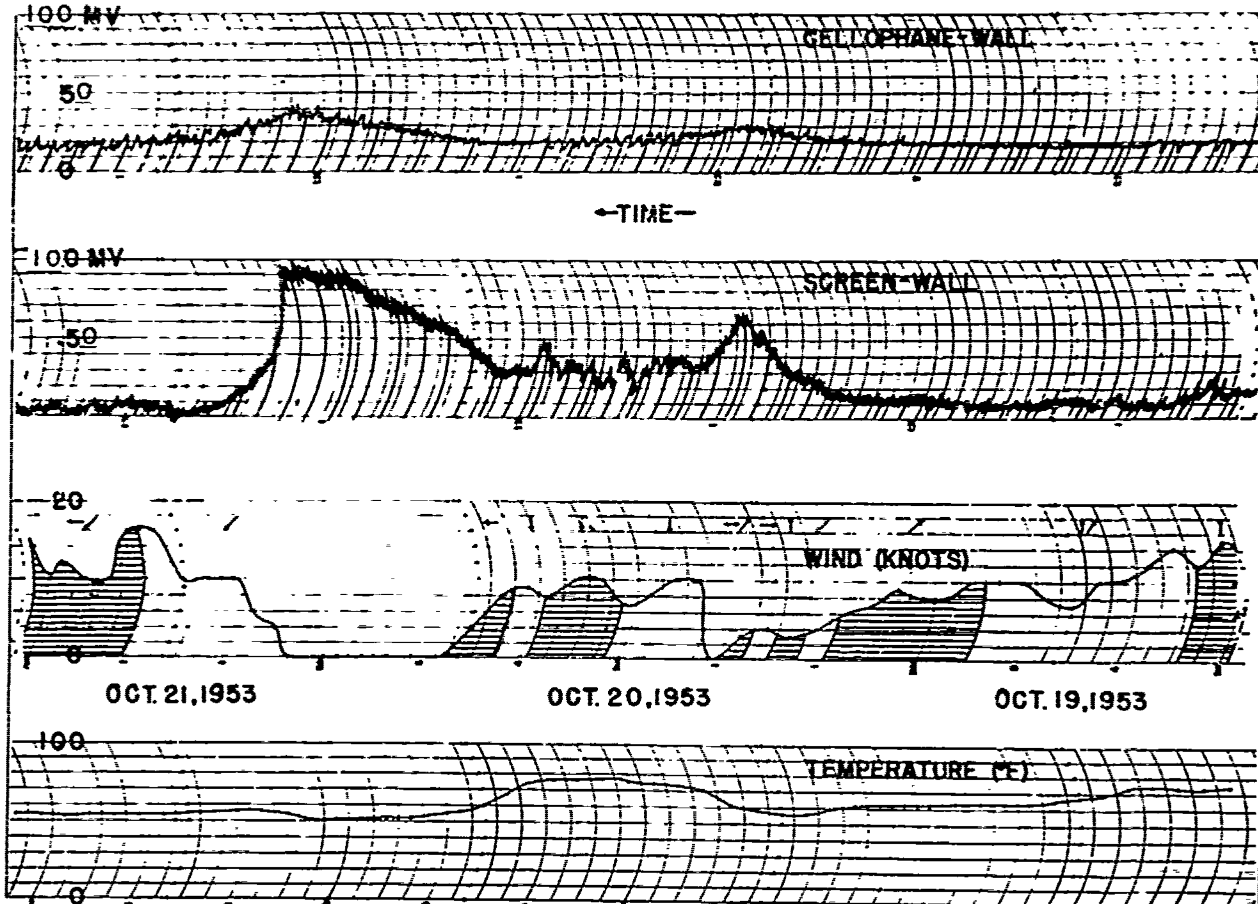


Fig. 8--October 19-21, 1953; full scale screen-wall ionization = 72 I; full scale cellophane-wall ionization = 46 I

factor in producing diurnal variations, as expected. The short-period fluctuations in the cellophane-wall record are due to the effects of the heaters in the truck on the teflon insulator. During 1952, when an amber ' sulator was used, such effects were never observed. Unequal expansions of the insulator and the surrounding parts of the chamber apparently produce strains which induce a potential on the electrode, an effect which is more pronounced with teflon than with amber.

The records for October 19-21, 1953 (Fig. 8) show that at about 08h 00m on October 20 a wind shift occurred at the site, and for a short period there was no wind at all. As can be seen on both ionization records, an increase in emanation resulted immediately. The values before and after this maximum seem to indicate a difference between the readings for north and south winds. It is noteworthy to point out that north winds pass over wooded land while south winds pass over the runways, roads, and buildings of the air base. A large maximum developed during the next night, but was abruptly cut off at about 01h 30m when the new air mass began to dominate the area and pressures rose significantly.

Figure 9 shows the data for October 23-25, 1953. By October 23 a low pressure system had become dominant and light rain was falling at the site. One sees that even under these conditions the ionization record shows correlation with decreases in wind velocity. On October 24 the pressure

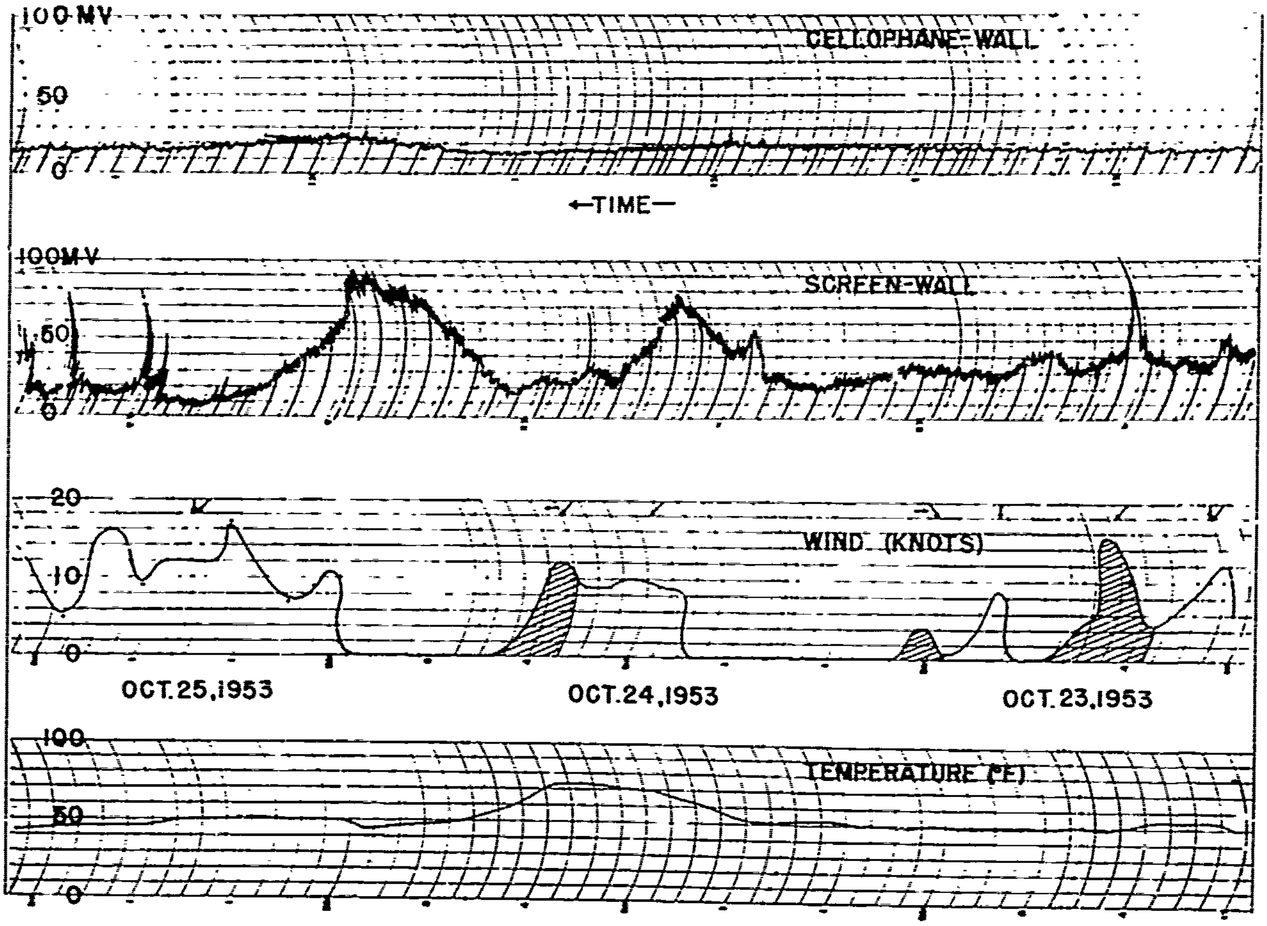


Fig. 9--October 23-25, 1953; full scale screen-wall ionization = 72 I; full scale cellophane-wall ionization = 46 I

rose again and a characteristic nocturnal maximum began that night. At midnight, however, the wind began and reduced the emanation content quite rapidly. Light rain at the end of the period gave several sharp fluctuations characteristic of rain showers.

A frequency plot (Fig. 10) shows the time difference in hours between the minimum nocturnal temperature and the ionization maximum, where positive values indicate a temperature minimum prior to the ionization maximum. Also indicated are time differences between the beginning of the wind on such days and the ionization maximum. It is clearly indicated that the ionization maximum occurs most often 1-2 hours after the surface heating begins, and that the decrease from the maximum is quite closely associated with the onset of wind for days when nocturnal calm prevails. As stated previously these results apply only to such cases. Of course, trapping of emanation occurs even when the wind does not decrease to such an extent; however, with the instrumentation available such cases could not be treated. An ideal arrangement would be a series of instruments on a tower which could measure simultaneously, at several heights, the ionization, the temperature, and the degree of turbulence. However, as yet such an arrangement has not been possible here.

<u>Discussion of results</u>--Having available only surface observations, it is difficult to apply these results to the general problem of the height distribution of emanation. LETTAU [1941, 1949] has

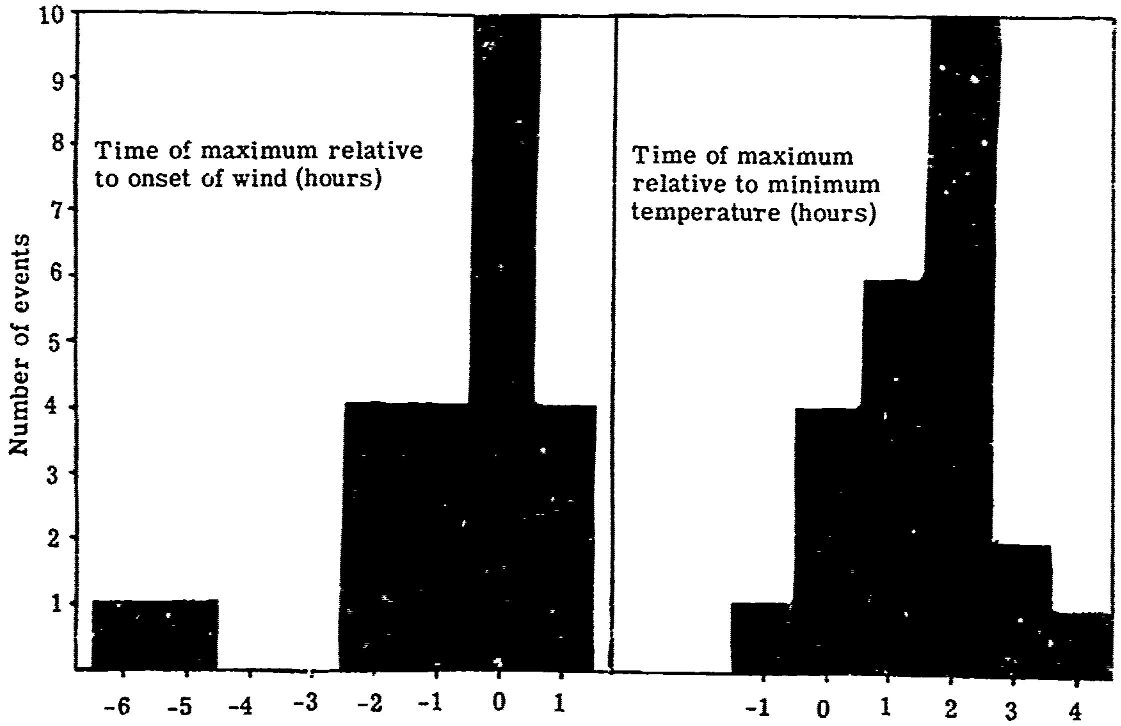


Fig. 10--Frequency plot of time of significant diurnal changes with respect to wind onset and temperature minimum (positive times indicate delay of ionization maximum)

solved the well-known diffusion equation for radioactive matter using the assumption that in the surface layer

$$A = A_0 + A_1 Z \qquad (Z \leq h)$$

where A is the exchange coefficient in gm/cm sec, and Z is the altitude in centimeters. The result, discussed in Lettau's paper, shows that such an assumption leads to an ordinary Bessel equation. The solution of this equation for various exchange conditions demonstrates that the concentration of radium emanation in the surface layer is nearly constant. However, A_1 is quite different for nighttime inversions and daytime convection, as is also the height of the surface layer. We shall assume Lettau's estimates of these values, where h is the height of the surface layer:

For strong convection	$A_1 = 0.02$ gm/cm^2 sec, h = 200 meters
For nocturnal inversion	$A_1 = 0.004$ gm/cm^2 sec, h = 50 meters

We can then calculate simply the order of magnitude of emanation content for the two conditions. If E is the exhalation in curies/cm^2 sec, and S the radioactive content in curies/cm^3, we can derive from the continuity equation an expression for equilibrium in a surface layer column of air of unit cross section

$$E = \int_0^h \lambda \, S \, d\, Z - \int_0^h \frac{1}{\rho} \frac{dA}{dZ} \frac{dS}{dZ} \, dZ \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where h is the height of the column, λ is the disintegration constant, ρ is the air density and A is the exchange coefficient. (We have neglected a term in d^2S/dZ^2.) The gradient of S at the top of the column is a critical factor in this problem. Its evaluation is difficult, particularly in this case, since the emanation content changes rapidly above the surface layer, but is almost constant within

it. We shall assume therefore, that within the surfa. layer $S = S_0 + S_1 Z$ when $Z \leq h$, where $S_0 \gg S_1 Z$. Thus

$$E = \lambda S_0 h - \lambda S_1 h^2/2 + (A_1 h/\rho) S_1$$

$$E \cong \lambda S_0 h + A_1 h S_1/\rho$$

so that we get

$$S_0 = [E - (A_1 h/\rho) S_1]/\lambda h \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Putting the values in this expression for strong convection, with $E = 40 \times 10^{-18}$ curies/cm^2 sec, $\lambda = 2 \times 10^{-6}$ sec^{-1}, and assuming S_0 is about 400×10^{-18} curies/cm^3 during the day, we obtain a value for the gradient

$$S_1 = 0.7 \times 10^{-22} \text{ curies/cm}^4$$

During the nocturnal inversion, when equilibrium has been reached, the decrease in layer depth alone will cause the gradient to increase. Thus, we take S_1 to be about 3×10^{-22} curies/cm^4, and solve for S under the nocturnal conditions. We obtain

$$S_0 = 3500 \times 10^{-18} \text{ curies/cm}^3$$

and the ratio of night to day readings is $3500/400 \cong 9$. This agrees with the order of magnitude of the average observed ratio of night to day readings, although several are larger than this by a factor of two. However, variations in exhalation, in the height of the surface layer, and in the gradient can all produce changes in this ratio quite easily. Qualitatively, one has an understanding of the process from (2); the formation of quite dense emanation layers can be explained by simple flux considerations in the layer, coupled with the effects of radioactive disintegration.

A detailed study of these variations could be carried out with instruments at various heights, so that the gradient of emanation content could be measured, as well as the thermal stratification which is responsible for these phenomena.

References

BECKER, F., Messungen des Emanationsgehaltes der Luft in Frankfurt a. M. und am Taunus-Observatorium, Beitr. Geophys., v. 42, pp. 365-384, 1934.

BLIFFORD, I. H., L. B. LOCKHART, and H. B. ROSENSTOCK, Radioactivity of the atmosphere, Naval Research Lab. Rep. no. 4036, 1952.

CULLEN, T. L., On the exhalation of radon from the Earth, Terr. Mag., v. 51, pp. 37-44, 1946.

HESS, V. F., and R. P. VANCOUR, The ionization balance of the atmosphere, J. Atmos. Terr. Phys., v. 1, pp. 13-25, 1951.

HOGG, A. R., Continuous observations of the rate of production of small ions in the atmosphere, Beitr. Geophys., v. 43, pp. 359-378, 1935.

LETTAU, H., Anwendung neuerer Ergebnisse der Austauschlehre auf zwei luftelektrische Fragen, Beitr. Geophys., v. 57, pp. 365-383, 1941.

LETTAU, H., Isotropic and non-isotropic turbulence in the atmospheric surface layer, GRD Paper no. 1, U. S. Air Force Cambridge Research Center, 1949.

MACEK, O., and W. ILLING, Messung des Emanationsgehaltes der Luft nach der Spitzenmethode, Beitr. Geophys., v. 43, pp. 388-418, 1935.

PRIEBSCH, J., G. RADINGER, and P. L. DYMEK, Untersuchungen über den Radiumemanationsgehalt der Freiluft in Innsbruck und auf dem Hafelekar (2300 m.), Beitr. Geophys., v. 50, pp. 55-77, 1937.

WAIT, G. R., Some experiments relating to the electrical conductivity of the lower atmosphere, J. Wash. Acad. Sci., v. 36, pp. 321-343, 1946.

WILKENING, M. H., A monitor for natural atmospheric radioactivity, Nucleonics, v. 10, no. 6, pp. 36-39, 1952.

DISCUSSION
CONCERNING THE PAPERS PRESENTED ON THE MORNING OF MAY 19, 1954 AND RELATED ATMOSPHERIC ELECTRICAL PHENOMENA

H. Israël presiding

Dr. Israël--This morning we had some very interesting papers on atmospheric electricity and its relation to meteorology. The session this afternoon will be open to specific discussion on the experimental techniques and results of the work described this morning. It will also be open to general discussion on problems in this field.

Dr. Barklie--I would like to have Dr. Koenigsfeld explain how his instrument worked in a little more detail.

Dr. Israël--I believe Dr. Chapman has a similar question?

Dr. Chapman--Yes. Do I understand that Dr. Koenigsfeld used two separated radioactive collectors?

Dr. Koenigsfeld--In measuring the potential gradient we used two polonium collectors separated by a vertical distance of about two meters. The collectors were suspended from a balloon by a nylon cord 100 m long. One collector was connected to the plate of a triode and the other to the cathode so that the plate was normally at a negative potential with respect to the cathode. The cathode-grid current was passed through an inductance coil which is part of the oscillating circuit of the radiosonde. Variation in the current changed the frequency of the transmitted signal. The system could measure either sign of potential gradient. The time constant of the radioactive collector system was about three seconds.

Dr. Swann--In connection with potential gradient measurements, I would like to refer to a suggestion I made a number of years ago for eliminating the effect of charges on the apparatus. Consider a body of any shape and charge distribution attached to a cavity C. We observe that if this apparatus is put into an extensive uniform field X, the field inside C will be independent of all that concerns the charge on it other than the charge distribution induced by X, and thus, it will depend only upon the geometry of the whole system and upon the field X. The field in C may be small but there is no difficulty in measuring small fields. The apparatus can readily be standardized by the use of a small scale model.

With regard to V. J. Schaefer's paper on the Observations of Atmospheric Electricity under Jet Streams, I would point out as follows: Suppose we have one gram of radium giving 3×10^{10} alpha particles per second. This gives about $2 \times 10^5 \times 3 \times 10^{10} = 6 \times 10^{15}$ ions/sec which corresponds to about $6 \times 10^{15} \times 5 \times 10^{-10}/3 \times 10^9 = 10^{-3}$ ampere. A millicurie would give 10^{-6} amp. If the field near the disc is such that from the five centimeter range of the alpha particles all the ions are collected, the current obtained is simply representative of the foregoing. If there is wind, that which is measured is something depending upon wind, collector size, height, etc.

I suggest that in using values for ionization per cc due to cosmic rays, we calculate the results from the data on the number of rays rather than from ionization chamber measurements.

Dr. Weickmann--With regard to the increase and decrease of potential gradient at high altitudes reported by Dr. Koenigsfeld particularly at the -32°C level, I should like to mention some aircraft measurements carried out by Dr. aufm Kampe and myself. We found that quite often haze layers occurred up to 10,000 m. It may be that the fluctuations measured are connected with such haze layers. They may also be connected with cirrus clouds which occur correspondingly quite often in

layers and whose base temperature was found to be at the -31°C level on the average. Since the individual base temperatures, however, varied between about -15° and -50°C, one cannot say that the -31° level was an especially significant one.

Dr. Gish--This morning I was reminded of some of our own difficulties in aircraft measurements of atmospheric electrical elements when we entered clouds or regions containing particulate matter.

In our flights over the Pacific and the southwestern United States we first noticed the effect of haze and cloud droplets on air conductivity measurements. If solid particles impinge on the central electrodes of two Gerdian tubes, one measuring positive and one, negative conductivity, the charge imparted to the electrodes will cause the apparent conductivity of one sign to rise and the apparent conductivity of the other sign to fall. In order to recognize this effect it is very important to have two conductivity equipments in aircraft measurements.

The ratio of positive to negative conductivity in the general vicinity of thunderstorms varied considerably. This ratio was usually greater than unity at altitudes lower than about 20.000 ft and it tended to be less than unity at higher altitudes.

For these reasons, except on clear days, one must not place too great confidence in the precision of conductivity measurements.

Dr. Israël--I believe that Dr. Hogg has a question with respect to large ion content and the conductivity.

Dr. Hogg--In regard to Mrs. Sagalyn's paper, is it necessary to measure the background with still air in the apparatus, and secondly, would there have been a sufficient number of points on the characteristic of current against voltage in its normalized form to show whether there was any indication of definite species of large ions?

There is yet a third question, regarding the variation of conductivity with height.

Mr. Gish in his work showed this to be expressed by a quadratic formula. Would your results be approximated by this simple equation?

Mrs. Sagalyn--I shall try to answer Dr. Hogg's questions in order. First, the background signal for the three ion counts used in these experiments is measured and subtracted from the total signal. It is obtained by shutting off the air flow in flight by means of a remotely controlled air valve.

Second, the contribution to the total ion content (with mobilities between 0.7 and 2×10^{-4} cm^2/sec volt) of charged particles in the mobility region 0.7 to 5×10^{-3} cm^2/sec volt is usually found to amount to not more than ten per cent. The mobility at which the maximum concentration occurs is about 8×10^{-4} cm^2/sec volt.

Third, the conductivity distribution in the exchange layer does not follow a quadratic relation either in the mean or for individual days. Above the exchange layer the distribution roughly follows a quadratic relation.

Dr. Gish--It should be pointed out that the quadratic formula is an approximate empirical expression which was useful in presentation of the thunderstorm results where high precision was not required. The quadratic relation is not a good fit for the stratosphere data.

Dr. Bricard--What was the effect of charge on the aircraft in Mrs. Sagalyn's measurement of conductivity?

Mrs. Sagalyn--The effect of aircraft charge on conductivity measurement has been investigated and the results have been reported in the Journal of Geophysical Research in 1952. Briefly, the normal fair weather charge has a negligible effect on the measurement of conductivity of either sign.

Dr. Weickmann--In connection with Mrs. Sagalyn's measurements I wish to call attention to some aircraft measurements of the number of condensation nuclei which I have recently made using an Aitken nucleus counter. This counter was kindly loaned to us by the Carnegie Institution. The number of nuclei versus altitude shows the same characteristic as the number of large ions. A marked 'exchange layer' has a nucleus concentration between 10^4 and 10^5 per cm^3. Above this layer the concentration drops to 10^2 to 10^3 per cm^3.

Dr. Israël--Dr. Chapman, you have a question on the conductivity measurements in the free atmosphere?

Dr. Chapman--In Dr. Stergis' measurements, the conductivities on ascent and descent were different, and it was thought the difference might be attributed to electrostatic charge on the balloon. In Dr. Koenigsfeld's radiosonde data there was no evidence of influence of electrostatic charge on the balloon. Now then, why are some balloons charged and some not charged, or is this a meaningful question?

Mr. Coroniti--In Dr. Stergis' and my balloon experiments, all of our ascent data showed considerable variation. Of the eight flights we made, on only two flights going up did the experimental data fit the theoretical curve. I think that the variation is due in a very small part to the charge of the balloon. If the effect had been large, it would have been reflected in the ratio of positive to negative conductivities. This was not the case.

Dr. Chapman--I am glad to hear this because it has been my opinion that if the balloon were far enough away, the charge ought not to have much effect.

Dr. Curtis--I have one point to make here. The instrument on ascent passes through a volume of air which previously passed the charged balloon. The swinging of the instrument through this volume might have an effect, other than the electrostatic field effect.

Prof. Koenigsfeld--Yes, but it is very small when the instrument is between 100 and 200 m below the balloon at that angle.

Mr. Coroniti--I wish to make a comment on this morning's presentation of our papers. I believe one of our sources of error was the change of air speed through the conductivity tubes as the equipment oscillated like a pendulum about the vertical. This is important because we were operating close to the knee of the current-voltage curve.

Dr. Israël--Dr. Parkinson has a question on Dr. Stergis' paper.

Dr. Parkinson--My question is this: Dr. Stergis mentioned a theoretical saturation voltage for the Gerdien conductivity meter. This infers that you must know the mobility, and I wondered if you have any data on the mobility?

Mr. Coroniti--We have no direct mobility measurements. In selecting the value of the collecting voltage we computed the mobility using standard atmospheric tables.

Dr. Parkinson--This question of mobility interests me because from the data that I took in 1947, I got very strong evidence for a diurnal variation in negative small ion mobility which suggests some sort of change in the nature of the ion during the day, and I wonder how the nature of ion changes with altitude and I wonder how reliable the theoretical values of mobility are.

Dr. Israël--We shall now turn to questions concerning the measurement of electrical conductivity at surface stations of different altitude.

Dr. Kuettner--Did you extend your measurements over more than one year, Dr. Schilling? And did you get any seasonal changes? It would be surprising if you did not, because practically all meteorological elements, such as cloud types, travel up and down more than 10,000 ft during the year. From your curve, it was not quite clear whether this is an average value for the whole year.

Dr. Schilling--Our measurements extended over more than a year. Unfortunately, we have no definite information of the variation as a function of the season because the data was taken intermittently during two or three seasons. I am quite sure there is a variation with season. We have some indications, of course, but I don't think that I want to make any definite statements at this time.

Dr. Israël--Dr. Nolan wishes to discuss this problem.

Dr. Nolan--In Dublin it was found that the most important element affecting the RaA content of the atmosphere was wind. Under calm conditions high values were obtained, with increasing air movement the content diminishes. The atmospheric conditions which favored high values of RaA content favored high values for the concentration of nuclei, and conversely. A considerable portion of the RaA carriers have mobility between 0.045 and 0.015 cm/sec volt/cm. With high content of RaA and high nucleus content carriers of lower mobility appear. The associated variation of the radioactive and nucleus content of the air may partially explain Dr. Schilling's results on conductivity.

Mr. Cotton--I was interested to know whether Dr. Schilling thought there was some preferential mechanism of attachment of the radioactive material to the large particles.

Dr. Schilling--To answer this, actually, I have to refer to Dr. Israël's laboratory experiments in 1934. He mentions selective absorbtion of radioactive substances by aerosols. I wonder whether you wish to comment on this, Dr. Israël.

Dr. Israël--My experiments indicated that there was a close connection between the radioactive content of the atmosphere and the concentration of nuclei.

Dr. Nolan--In Dublin large values of radon content are associated with large values of nucleus concentration. Conditions which keep radon near the ground act in the same way on the nuclei. This phenomenon would tend to produce the result found by Dr. Schilling--that the conductivity appears to be independent of local conditions.

In Dublin it was found that radon was removed from air by passage through a cotton-wool filter. This is in disagreement with the results of Hess.

Mr. Reynolds--I think I should ask this question of Dr. Schilling and Dr. Israël. I am not clear as to how one resolves the fact that the conductivity seems to be independent of local conditions and yet the potential gradient over the ocean seems to have a different diurnal pattern than it does over continental masses. This is true, is it not?

Dr. Schilling--If our ideas are correct, it is a variation of nuclei plus a variation of radioactive content. This would be different over land and over sea, which is in a way the answer.

Mr. Reynolds--I think maybe this explains why the conductivity does not vary greatly, but I then do not see how the potential gradient could have one diurnal variation over the oceans and a different one over the land masses. If the conductivity is not affected by local conditions, how is a potential gradient affected by local conditions?

Dr. Holzer--I believe that the potential gradient is affected by the conductivity, and where the layer affected is thin, it is well known that there is almost a reciprocal relation between the potential gradient and the conductivity. The fact that the mean conductivities show a consistent variation with altitude does not indicate that the conductivity is constant during the day. Therefore, there is no implication that the variation of potential gradient during the day should be the same over land and sea.

Dr. Gish--On that point, we had many years of record at Carnegie Institution of Washington on conductivity measurements both positive and negative and potential gradient, and we can compute the air-earth current density. The air-earth current density as a rule has a different variation more nearly like that on the ocean than elsewhere, which is in line with what Dr. Holzer said. That is certainly a conspicuous feature seen for years at three or four observatories for which we had records. Our records indicate to me that the diurnal variation of conductivity at our observatories depends largely upon the local environment.

Dr. Israël--We come to the paper of Dr. Schaefer. There are some comments, I believe. Dr. Hogg.

Dr. Hogg--Is there any correlation between the meteorological corona observed around the sun and the high readings given by your apparatus in clear weather?

Dr. Schaefer--We have attempted correlations but the situation is very complicated. There are times when the effect may be produced by dust which may be local or from some distance away. Local dust produces a negative current. Dust from distant areas may reach considerable heights in the atmosphere and at sufficient altitude may serve as nuclei for ice crystals. When our currents are largest, there is usually little scattering near the sun and visibility is unusually high.

Dr. Kuettner--I have two questions. First, I have heard that you measure a change of sign of the current across the jet stream. Is it correct that either you or Falconer measure different signs of current north and south of the jet stream?

Dr. Schaefer--A very simple answer is no. In some cases when the jet stream moves northward and is followed by warm air accompanied by low, water clouds, there is a tendency for the current to become negative under the clouds.

Dr. Kuettner--My second point relates to the attempt to correlate the high fair-weather current and the jet stream. Those who have tried other correlations with the jet stream know that there are several difficulties. There is no general agreement with respect to a definition of the jet stream. If one defines the jet stream as the region of maximum wind, shown on facsimile maps as an arrow, one finds that the 'jet stream' is within 200 to 300 miles of Boston and Albany on 60 to 70 pct of all days. It is probably desirable to use a more stringent definition of 'jet stream': a narrow band with very limited vertical and horizontal extent with extremely high winds. I wonder if you could call your analysis a correlation with strong upper winds rather than with the jet stream.

Dr. Schaefer--In making observations of atmospheric electricity under jet streams the correlations obtained were related to the WBAN isotach high level charts showing the wind field and indicating the major axis of jet streams. Much of this work was done by R. F. Falconer of the General Electric Research Laboratory who found a highly significant correlation. It should be emphasized that there are many things we do not know about these manifestations, particularly the sensitivity of the method for localizing the major axis of the jet. What is needed is a fairly dense network of stations which are placed so as to be at right angles to the flow in a region where jet passages are common. Because of the relative simplicity of the method described it is hoped that such a network will be feasible.

While it is true that our data are not conclusive at present for telling the difference between a jet stream passage or just a general movement of high winds, it is believed that the evidence at present is highly suggestive. The paper was presented to call the attention of specialists in the field of atmospheric electricity to a new possibility for the use of this phenomenon.

Evidence has also been found that the initial formation of clouds immediately above the radioactive probe have a tendency to depress high values if they are occurring in association with a jet stream. Thus a current flow of 0.05 microamps may drop temporarily to 0.015 while the newly forming liquid droplet cloud is above the station.

Mr. Reynolds--One has to separate electrical effects of clouds from those due to the jet stream. Effects due to precipitation in associated clouds might confuse the correlation with the jet stream.

Dr. Schaefer--This, I think is one of the most attractive features of these studies--the differences which occur. With this simple device we may observe a number of effects which clouds produce. It should be possible to obtain observations to determine whether the observed effects are related to early stages of cloud formation.

Dr. Chalmers--There are one or two points that I want to raise. First of all, I would ask Dr. Schaefer whether he has tested his measuring apparatus against more ordinary field machines to see whether it does give the field or anything more. It seems to me the radioactive ionization is going to be affected by the wind particularly if you use radium. It is important to know whether you get the same results with ordinary field measuring apparatus.

Dr. Schaefer--In the early phases of our work some attempts were made to calibrate our point collector with the more conventional instruments. This was not carried to a satisfactory conclusion due to lack of time and the inadequacy of instrumentation. Since the point collector is such a simple device, it is suggested that it would be very desirable for several specialists in this field who have field meters to make such comparisons. I would be glad to cooperate.

Dr. Swann asked me in the morning the quantity of radium used on the point collector. This is approximately 250 micrograms and has a surface area of about 1.6 cm^2.

Dr. Chalmers--We have used a field measuring device in conjunction with a photoelectric cell mounted in a vertical tube to correlate the electric field with cloud brightness. In stratocumulus clouds the thicker portion contains more negative electricity and the thinner parts less. This does not quite correlate with your measurements but it may be somewhat similar. We also have made fine weather measurements and we have not observed anything which clearly corresponds to your observations.

Dr. Schaefer--About the best I may say in comparing the records, is that a simple radioactive point compared to more complicated field measuring instruments produces the same kind of records in a qualitative way. In other words, the variation in sign and relationships during passages of fronts and other meteorological phenomena gives us the same picture. I believe the main interest in this device is the simplicity of getting measurements of atmospheric electricity even though its calibrations may be very complicated.

Dr. Wormell--I think that it is important that Dr. Schaefer's observations and results should be interpreted in terms of more fundamental quantities. The current in the radioactive point will depend on the intensity of the field in the space immediately surrounding the point, that is, it will be a complicated function of the potential gradient and of the distribution of space charge; the latter will depend on the wind. The observation that the effect near jet streams requires also a strong surface wind suggests that the latter is required to blow away the charge coming from the point.

A quiescent cloud, containing no particle of perceptable size, can affect the potential gradient in two obvious ways. If all the particles are very small, the main effect is simply to reduce greatly

the conductivity throughout the cloud layer. This will reduce the vertical current and ultimately the potential gradient near the ground. If the cloud contains particles whose velocities of fall exceed about 1.5 cm/sec, they will capture negative ions selectively in the normal fine-weather field and the lower part of the cloud will tend to become negatively charged. This process may conceivably reverse the normal field. They appear to be observed with some, but by no means all, small cumulus.

An enhanced field near the ground, when a zone of strong wind is overhead but the sky is quite clear, is more difficult to explain. It implies an enhanced vertical current. Is it conceivable that the converging of the air stream at high levels to form the jet has caused an enhanced supply of ions to be fed in overhead, thus giving an increased current?

Dr. Israël--Are there further individual questions or comments on the various papers? If not, we should have a general discussion now on the problems presented in the papers of this morning.

Dr. Byers--I was gratified to note in these papers a presentation of electrical properties of the atmosphere in three dimensions. Meteorologists, as most geophysicists, are interested in the atmosphere as a whole. Vertical and geographic distributions such as those obtained by the Carnegie Institution are needed.

Dr. Gish--I want to make one statement following what Dr. Byers said. I like to think of the statement that was made by Lord Kelvin in connection with atmospheric electricity, that we need a geoelectric survey of the Earth just as we need a geodetic survey of the Earth.

Dr. Chalmers--Space charges in the lowest few hundred feet have a considerable effect on the field as measured at the Earth's surface. By the use of two field mills separated by 100 m in the direction of the wind, effects have been found which are explained by space charges moving with the wind. Some of these are due to puffs of smoke from railway trains, others are probably due to convection cells or 'bubbles' of diameters of the order of two km. Atmospheric electrical observations may serve to give information about air motion in the absence of clouds.

Dr. Holzer--Before discussing my principal point, I wish to say that Dr. Schilling and I have made a few measurements with two field measuring devices, one downwind from the other. We have obtained some results which tend to corroborate Dr. Chalmers observations. I feel that measurements of the type Dr. Chalmers described offer a very interesting approach to small scale meteorological phenomena.

Mr. Wyckoff, Mr. Coroniti, and I have been discussing the desirability of making atmospheric electrical measurements at altitudes greater than those which may be reached with high level sounding balloons, particularly between 35 km and the ionosphere. This region of the atmosphere can be explored by rockets but the measurements are time consuming and costly. Therefore, it seems appropriate to ask the opinion of members of this group with respect to the desirability of making the effort.

The recent measurements of conductivity made with sounding balloons and described here this morning suggest that the conductivity increases up to 30 km as it would be expected to if it were due to cosmic ray ionization. The conductivity may, of course, continue to increase in like manner up to the D region with no exciting anomalies. However, there is the interesting possibility that an anomaly may exist near the temperature minimum at 80 km. At high latitudes noctilucent clouds are observed at this level and recently Miley of the Geophysical Research Directorate has obtained photographs of clouds between 70 and 80 km at White Sands using rocket-borne cameras. If such clouds, not visible from the surface, are a persistent feature of the atmosphere, they would create a layer of low conductivity at night when the D layer is dissipated by recombination.

In regions of the high atmosphere where there are no significant particle concentrations, the measurement of conductivity or ion density together with cosmic ray ionization would provide a means of measuring the ionic recombination coefficient at low pressures. This cannot be done conveniently in the laboratory because of apparatus walls.

Measurement of the electric field at high altitude would be more difficult because it is certain to be small and because the rocket will in general be charged.

I have mentioned only two or three examples of high altitude measurements in the hope that some of you may wish to offer alternate suggestions or to express an opinion with respect to the value of these measurements which require considerable effort.

Mr. Burnight--Dr. Holzer's comments on such experiments on conductivity, potential gradient, and air glow are well founded. Such experiments have been performed by the Naval Research Laboratory in a preliminary fashion sufficient to provide some data establishing the feasibility of such a program of investigation. Over five rocket flights beginning as early as 1947 have been successful in providing interesting results. At altitudes above 70-90 km, the interpretation of these experiments becomes very difficult; therefore, this work should be intensively studied and expanded.

Dr. Israël--Are there questions too?

Dr. Fuchs--I refer to the words of Professor Holzer and should like to say a few words about the problem he mentioned. The noctilucent cloud layer, is of greatest interest for it is situated between the lowest part of the ionosphere and the upper-most boarder of the ozonosphere.

Therefore, all that happens in this thin region is of outstanding interest. We have not only to understand thermodynamical events therein, but also their origin. At the moment, very little is known about this region and I may draw your attention only to the fact that this level is also that of the reflection of the very long radiowaves, the only ones which in long-distance transmission are very little affected by disturbances due to solar flares. You know the practical importance of this problem and also the extensive work done in forecasting the variation of the electromagnetic behavior of this reflecting layer.

Furthermore, this region is that which regulates or controls the propagation of the click sferics produced by lightning flashes.

If you intend to help those men who have to make forecasts for this practical purpose and others, you must not forget to deliver to them the knowledge they need about the physical status and the thermodynamical behavior of this 80-kilometer region. Our knowledge of this region is small. The very seldom possible observation of the noctilucent clouds is the only one which gives us a little knowledge about the direction of air mass transport in these regions.

This is much too little and, therefore, it is high time to use new and effective means to increase our knowledge about this physically, highly interesting region.

Dr. Israël--I thank you very much.

A SURVEY OF AIR-EARTH CURRENT OBSERVATIONS

A. R. Hogg

Commonwealth Observatory
Canberra, Australia

Abstract--Most atmospheric electric quantities have little more than local significance and reflect mainly meteorological, industrial, and domestic conditions at the place of observation. An exception is the world-wide simultaneous diurnal variation in potential gradient over the oceans which is attributed to changes in the potential V, of an upper conducting layer in the atmosphere.

The present work uses an equation for the variation of conductivity with height determined by Gish and Wait to fix a relation between the total conductivity at the ground (λ_0) and the air-earth current i. It is found that a parameter $a = i/\lambda_0{}^{0.5}$ should be statistically proportional to V. Accordingly mean values of a should show a parallel variation with the time even for widely separated stations. This is confirmed by an examination of results from Watheroo, Huancayo, and Tucson.

The aim of this work is to find some world-wide regularity amongst the many published observations of atmospheric electric quantities at various land stations. It is well known that the most frequently measured atmospheric electric quantity, the potential gradient, is subject to great fluctuations from station to station even on electrically quiet days and that, over land, the character of the variation changes from place to place in no very regular way. Even the habits of the population surrounding the station can influence the variation of the Earth's field as may be instanced by the change in standard time of the maximum at Kew with the introduction of summer time [WHIPPLE, 1929] or the excessive range of gradients encountered by SAPSFORD [1937] at Apia on Sundays during and after intensive cooking operations by the inhabitants.

Atmospheric electric conductivity over land is also subject to much variation from place to place. The conductivity depends on a balance between atmospheric ionizers, atmospheric pollution, and meteorological conditions and may change from place to place by a factor of 25 or so, again in a highly individual fashion. There is less variation in the air-earth current than in the other quantities but even here mean values vary by a factor of four or five from station to station and again, from rather scanty knowledge, the diurnal variation does not display any conspicuous regularity from place to place according to universal time, although there is a tendency for the quantity to be a maximum in the morning according to local time.

Outstanding regularities have been demonstrated by MAUCHLY [1926] in the results of the cruises of the Carnegie, namely, that over the oceans the diurnal variation of conductivity is negligible and that the variations of potential gradient and air-earth current at all places where measures were made during fine weather both follow the same diurnal course; that is a single wave with a maximum at about 20 hours GMT. This result has been confirmed by later work, TORRESON and Others (1946]. It supports the often-used model of the fine weather atmospheric electric process as a leakage current across the dielectric of a gigantic spherical condenser, with the Earth's surface as cathode and a conducting region in the upper atmosphere as anode. The conductivity of the anode region is sufficiently high compared with the conductivity to ground to ensure that changes in the potential of the anode region take place simultaneously or nearly so over the whole Earth. As well known, WHIPPLE [1929] following a suggestion by Appleton has been able to show that the world-wide variation of gradient over the oceans is in phase with the global variation of thunderstorm frequency. This, coupled with the more recent work of GISH and WAIT [1950] on the electric currents over thunder clouds, does much to support the idea of the thunderstorm as the major agency for maintaining the Earth's field.

Traces of the 'ocean' type of world-wide variation of potential gradient are found at land stations under conditions of presumably uniform conductivity. For example, ALLEN [1939], has found that on Mt. Stromlo the first harmonic of the potential gradient normally shows a maximum at 22-23h GMT, but on days of continuous wind, the variation more closely approaches the ocean type and shows a maximum about 19h GMT with a big reduction in the amplitude of the second harmonic. This again supports the idea of an upper conducting layer.

Obviously the common factor which will appear in all atmospheric electric potential or air-earth current results is the potential V of the conducting layer. This, combined with a concept developed by GISH [1944], namely, the columnar resistance of the atmosphere R (that is, the resistance of a unit cross section of the atmosphere between ground level and the conducting layer) determines the air-earth current i at any locality. Summarizing

$$i = V/R$$

Of these three quantities it is practicable to measure regularly only i; but an estimate of R may be obtained from the variation of conductivity with height. GISH and WAIT [1950] have shown from the results of the Explorer II ascent as well as from a number of aeroplane flights that the conductivity at a height h is given by expressions of the following form: for positive conductivity

$$\lambda_1 = \lambda_{01} + b_1 h^2$$

for negative conductivity

$$\lambda_2 = \lambda_{02} + b_2 h^2$$

where λ_{01} and λ_{02} are positive and negative conductivities at ground level respectively and b_1 and b_2 are constants which differ from each other. Accordingly without distinction of sign

$$\lambda = \lambda_1 + \lambda_2 = \lambda_0 + bh^2$$

Whilst λ_0 is relatively well known, information about b is scanty being effectively limited to the results quoted above where an average figure of $b = 44 \times 10^{-10}$ (for conductivity in units of $\text{ohm}^{-1}\text{cm}^{-1} \times 10^{-18}$ and h in cm) is given. The value of b may be expected to depend to some extent on meteorological conditions and to vary from place to place but probably to a less extent than say λ_0. The resistance at any height is

$$\rho = 1/(\lambda_0 + bh^2)$$

and the resistance of a column of the atmosphere of unit cross section up to a height h is

$$R_h = \int_0^h \rho\, dh = (b\lambda_0)^{-0.5} \tan^{-1} [h(b/\lambda_0)^{0.5}]$$

For large values of h (15 km or more) the value of the $\tan^{-1}$ term commences to approach its limiting value of $\pi/2$ and with a considerable degree of approximation it is possible to express the air-earth current as

$$i \approx 2/3\ (b\lambda_0)^{0.5}\ V \qquad (1)$$

With representative values of $\lambda_0 = 300 \times 10^{-18}\ \text{ohm}^{-1}\ \text{cm}^{-1}$ and $i = 250 \times 10^{-18}\ \text{amp cm}^{-2}$ and the value of b given above $V = 3.4 \times 10^5$ volt which is about the accepted value.

An objection may be raised to this method of approach because the conductivity of the upper portion of the atmosphere, is presumably controlled by the absorption of cosmic radiation and ionic recombination in clean air; that is, by mainly constant factors, whilst the conductivity of the lower layers, which contribute largely to the total resistance of the atmosphere, is greatly dependent on variable meteorological conditions and accordingly the total effect would need to be represented by

a more complex equation than that given above. Whilst this may be so, attention should be drawn to curves by WHIPPLE [1936] comparing the percentage diurnal variations of the columnar resistance over Kew with the specific resistance of air near the ground. Under both winter and summer conditions the two curves run largely in parallel except for a short period about 09h GMT (presumably before diurnal convection has become effective in dispersing the early morning pollution) when a maximum of resistance near the ground is not reflected in the columnar resistance.

To examine (1) it is convenient to define the quantity $a = i/\lambda_0^{0.5} \approx (2/3)\ b^{0.5}\ V$. It is not to be expected that a will necessarily be a constant, for b might vary from place to place and with the season, whilst V, although probably constant for all places at a given moment, might vary with the time. However, it might be expected that values of b at any one place over an integral number of years would be nearly constant and that V (as it averaged over the globe) would not vary greatly. Thus annual averages of a may be roughly constant. The relation is best shown by plotting annual means of i and $\lambda_0^{0.5}$ (Fig. 1). The derivation of this figure and the sources of the data are listed in another place [HOGG, 1950]. Some additional references have been made and figures revised using data given for Watheroo [TORRESON and WAIT, 1948], Huancayo [WAIT and TORRESON, 1948], and Tucson [WAIT, 1953]. The averages used are derived only from sets of observations which extend over a reasonably long period, at least twelve months and usually much longer. The results are not as homogenous as might be desired having been obtained by several different methods, and this could account for some of the scatter.

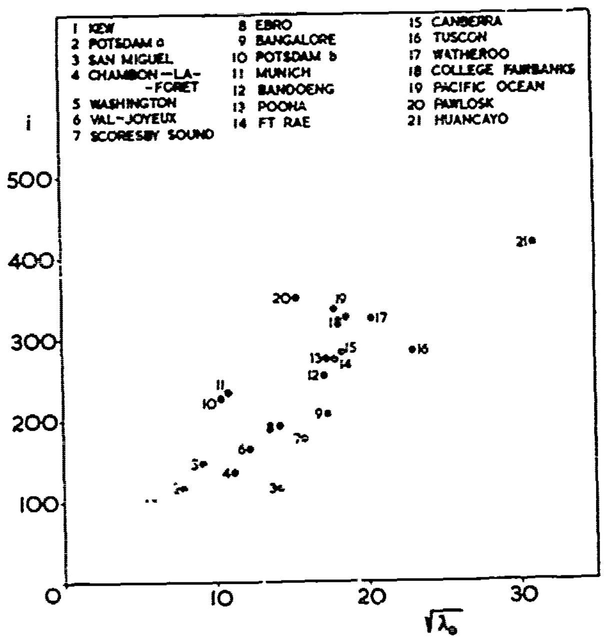


Fig. 1--Relation between station means of i and $\lambda_0^{0.5}$

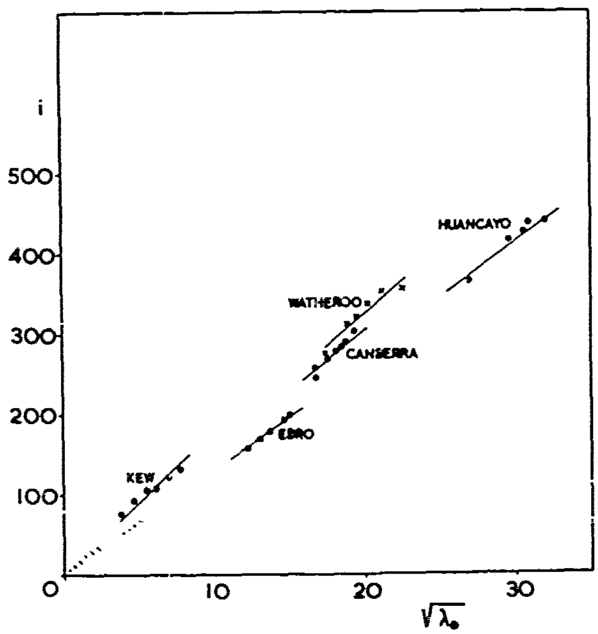


Fig. 2--Relation between i and $\lambda_0^{0.5}$ for single stations

The relation between i and $\lambda^{0.5}$ is also shown to some extent in results from a single station. Monthly averages of observations from one station were arranged in order of conductivity and divided into groups containing equal numbers of observations from which means were found. These are shown in Figure 2 for five stations. That the relation holds individually for the stations suggests that b and V or at any rate the product $b^{0.5}V$ does not vary much. It will be seen later that whilst V apparently undergoes regular increases and decreases these do not amount to more than a few per cent in the mean and this would not be very appreciable in Figure 2 even if changes in b did not occur.

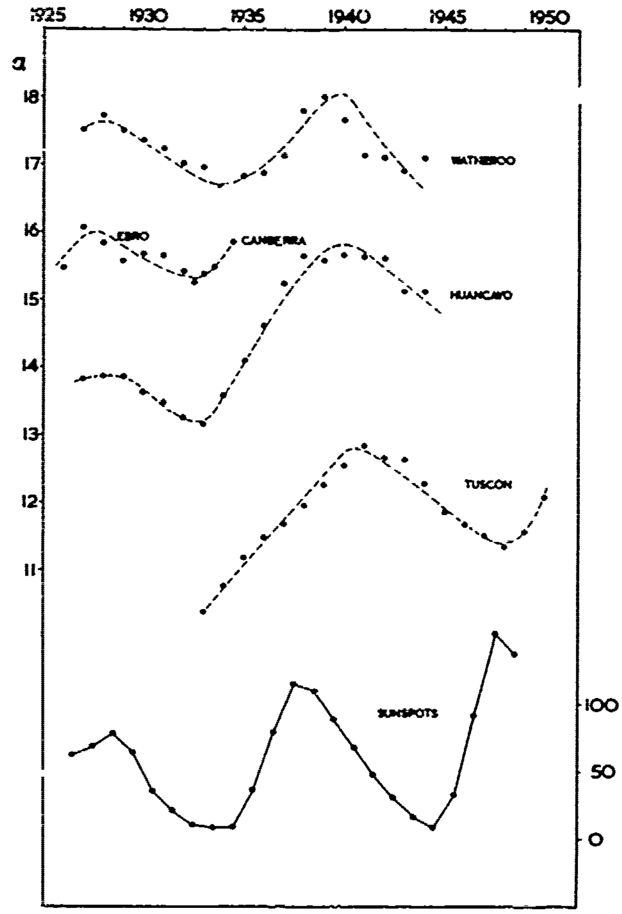


Fig. 3--Variation of a with time

The analysis offers the opportunity of examining long period variations in V. If values of a for any one place be averaged over a few years it might be expected that the effect of any random local fluctuations in b would be eliminated and that any residual systematic variation could be attributed to changes in V. In this case values of a obtained for different stations would show parallel variations with the time. Long series of observations suitable for this purpose are rare, especially as it is also required that they should be carried out at the different places by carefully standardized methods. Fortunately three homogenous sets of observations are available. They were obtained by the Carnegie Institution's equipment at the widely separated localities of Watheroo, Huancayo, and Tucson, where continuous recorders of similar pattern were installed. The annual means of $i/\lambda_0^{0.5}$ for these three stations have been worked out from the published data mentioned above and are shown in Figure 3 in the form of running means for periods of four years. This degree of smoothing appears to be necessary to remove chance fluctuations. Each point, therefore, represents an average of between 10,000 and 20,000 hourly readings. There is a remarkable similarity in the course of the curves for these three stations. At Watheroo and Huancayo, where the observations cover the same period, maxima occur in 1928 and 1940 with minima at 1933-34. The relative heights of the maxima differ at the two stations, the 1940 maximum at Huancayo being higher than the one at Watheroo. The Tucson results do not cover the same period but also show the maximum near 1940. Closer examination shows that the actual maximum plots at Watheroo, Huancayo, and Tucson occur in 1939, 1940, and 1941 respectively but recalling the statistical nature of the data it is likely that the three sets of figures could be represented by curves with maxima at 1940. Fragmentary data exist for Ebro and Canberra and, though of considerably less weight than that from the three main stations, support the general trend. A long series of results has been obtained at Kew (London) but is not used here because of the exceptionally high degree of atmospheric pollution existing at that station.

Normalized points (that is, percentage deviations from each station mean) for the concurrent portions of the data for Watheroo, Huancayo and Tucson are shown in Figure 4, along with a mean curve derived for all three stations. The correspondence is not exact but again the small range and the statistical nature of the results suggests that the results for the three stations might be fairly represented by a common curve.

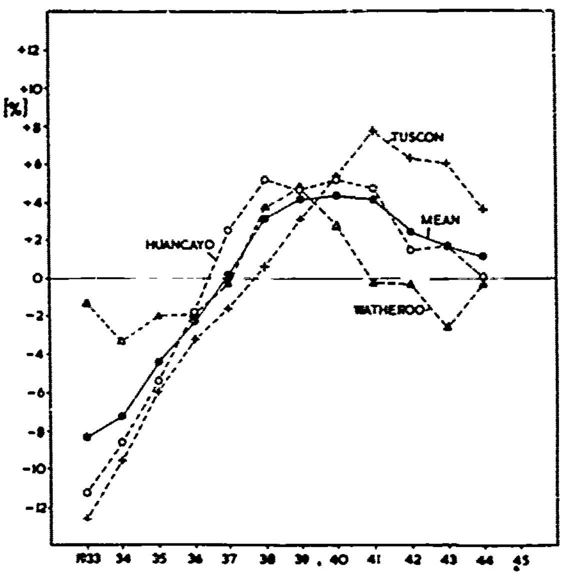


Fig. 4--Normalized variations of a

The curves of Figure 3 at first show a certain parallelism with the sunspot curve which is shown at the lowest curve of the figure. The coincidence of the maximum of a is good for 1928 but sunspot maxi um of 1938-1939 is somewhat in advance of the maximum of a, and by 1948 the curves are anti-parallel. The present results, like many other atmospheric electric observations, fail to demonstrate any conclusive solar-terrestrial relations.

References

ALLEN, C. W., Potential gradient observations at Mount Stromlo, during 1933-1938, Memoirs of the Commonwealth Solar Observatory, no. 8, pp. 1-32, 1939.

GISH, O. H., Evaluation and interpretation of the columnar resistance of the atmosphere, Terr. Mag. Atmos. Elec., v. 49, pp. 159-168, 1944.

GISH, O. H., and G. R. WAIT, Thunderstorms and the Earth's general electrification, J. Geophys. Res., v. 55, pp. 473-484, 1950.

HOGG, A. R., Air-earth current observations in various localities, Arch. Met. Geophys. und Bioklim. ser. A, v. 3, pp. 40-55, 1927.

MAUCHLY, S. J., Studies in atmospheric electricity based on observations made on the Carnegie, 1915-1921, Res. Dept. Terr. Mag., Carnegie Inst. Washington Publ. 175, v. 5, pp. 387-424, 1926.

SAPSFORD, H. B., Influence of pollution on potential gradient at Apia, Terr. Mag. Atmos. Elec., v. 42, pp. 153-158, 1937.

TORRESON, O. W., and G. R. WAIT, Atmospheric-electric results Watheroo Observatory, Western Australia 1924-1934, Res. Dept. Terr. Mag., Carnegie Inst. Washington Publ. 175, v. 17, 1948.

TORRESON, O. W., and Others, Scientific results of cruise VII of the Carnegie during 1928-1929, Ocean atmospheric-electric results, Oceanography III, Carnegie Inst. Washington Publ. 568, 1946.

WAIT, G. R., Investigation of electrical properties of the atmosphere, Appendix to final report, Air Force Cambridge Research Center, Contract No. AF 19(604)-251, 1953.

WAIT, G. R., and O. W. TORRESON, Atmospheric-electric results Huancayo Observatory, Peru, 1924-1934, Res. Dept. Terr. Mag., Carnegie Inst. Washington Publ. 175, v. 19, 1948.

WHIPPLE, F. J. W., On the association of the diurnal variation of electric potential gradient in fine weather with the distribution of thunderstorms over the globe, Q. J. R. Met. Soc., v. 55, pp. 1-13, 1929.

WHIPPLE, F. J. W., The influence of urban conditions on the circulation of electricity through the atmosphere. Trans. Faraday Soc., v. 32, pp. 1203-1209, 1936.

MEASUREMENT OF THE AIR-EARTH CURRENT DENSITY

H. W. Kasemir

Deutscher Wetterdienst
Meteorologisches Observatorium
Aachen, Germany

Abstract--There is no doubt today that the simultaneous registration of the atmospheric-electric field F, the air-earth current i, and the conductivity is necessary for the evaluation of atmospheric electric measurements. In this field the registration of the air-earth current i involves specific difficulties, not only with regard to the smallness of this current, but also because the conduction current is superposed on the large current of influence charges. This troubling influence current can be eliminated completely as may be shown theoretically and experimentally. From the Maxwell equation the following equation for the current J (through the measuring resistance) is deduced

$$J = (\theta/T)\,i + (1/T)[1 - \theta/T)e^{-t/T}\int i\, e^{t/T}dt$$

where t is the time, θ, the time constant of the atmospheric electric field at the measuring place, and T, the time constant of the input of the apparatus. The air-earth current i can be given as a function of time in any form. From this equation follows $J = i$, for $\theta = T$, that is, the current J flowing through the measuring resistance is identical with the air-earth current. The troubling influence currents, which are given by the second term of the equation, are compensated to zero. By a more electrotechnical substitute circuit diagram, the meaning of the condition $\theta = T$ is demonstrated. From the slow diurnal variations up to the quick variations of lightning flashes the recording of the air-earth current is independent of the frequency and correct in the amplitude. The registration apparatus is simple and the theory is clear so that the air-earth current is now accessible for the atmospheric electric technique of measurement.

For a long time it has been pointed out that simultaneous measurement of all of the three elements of atmospheric electricity is important. For the most part the potential gradient and the conductivity are recorded and the air-earth current is calculated from these elements. Normally, the expression 'air-earth current' is used for the conduction current whose carriers are ions moving in the direction of the electric field. This, however, should not be confused with the convection current which is carried by precipitation particles moving against the electric field and with Maxwell's dielectric current, commonly called 'influence current.' In the following discussion, we shall consider only the conduction and influence currents, but not the convection current.

A measurement of the air-earth current, that is, the conduction current, is very difficult since it is strongly disturbed by the influence current. In the following I will explain a method which yields a clean separation of the conduction current from the influence current. The air-earth current is usually measured by means of a plate exposed to the open air. This plate picks up the air-earth current which then flows through a calibrated resistance to the Earth and the voltage drop across the resistance is measured. With this method, the influence current is simultaneously being picked up. This effect is due to the existence of a capacity between the plate and the air. There exists also a certain capacity between the plate and the ground. Thus, a capacity lies parallel to the resistance of the air column above the plate as well as across the calibrated high resistance to the ground below the plate. We arrive at the following circuit diagram shown in Figure 1. The following is an explanation of the symbols used:

r = the resistance of the unit volume of the air

ϵ = the capacity of the unit volume of the air

R = the high ohm resistance to the ground

C = the capacity parallel to this resistance.

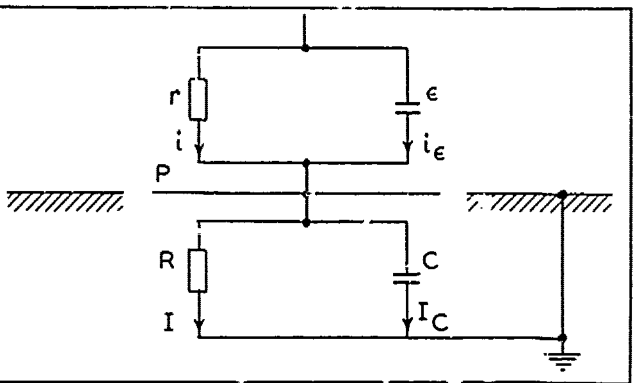


Fig. 1--Circuit for measurement of air-earth current

Normally C is only a few $\mu\mu$F but it may increase to much higher values up to 100,000 $\mu\mu$F by long cables or by the addition of commercial condensers. We will see how the accurate measurement of the air-earth current depends on the proper magnitude of the condenser C. ϵ represents the influence effect of the field and is identical with the dielectric constant. This dielectric constant is interpreted in our diagram as the specific capacity of the unit volume of air, as will be shown later. The input of the recording device (electrometer or the grid of an electrometer tube) is connected with the plate P.

Now we will calculate the currents which flow through each of the resistances. The idea behind these calculations is to find a circuit which allows only the air-earth current but not the dielectric current to proceed through the resistance r, the plate, and the resistance R. The dielectric current, on the other hand, should go through the condenser ϵ, the plate, and the condenser C. At first, the calculation will be given in general terms by solving the differential equation which is derived from Maxwell's equations. Later on, we will see that the same result can be obtained simply through application of Ohm's law using the circuit diagram. Here we start with the Maxwell equation

$$\partial\theta/\partial t + i = c = \text{curl } H \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The first term means the Maxwell dielectric current, i is the conduction current; consequently, c, the sum of both of these terms is the complete Maxwell current. Curl H is the rotation of the magnetic field. We take the divergence of (1) and obtain

$$\text{div } (\partial\theta/\partial t + i) = \text{div } c = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

divergence c = 0 indicates that for the unit volume considered the outflowing current c_2 must be equal to the inflowing current c_1. Thus, we arrive at the simple equation

$$c_1 = c_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

which means, mathematically expressed, the integration of (2).

This result will now be applied to our plate which is exposed to the air-earth current. The dielectric current $F\,\partial\theta/\partial t$ and the conduction current Fi flow through the plate with a cross section F. Flowing away from the plate are the currents I through resistance R and I_C through the capacity C. Consequently we get

$$F\,(\partial\theta/\partial t + i) = I + I_C \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

We are now interested in the current I through R as a function of the air-earth current i. Therefore, we have to try to eliminate from (4) the expressions $\partial\theta/\partial t$ and I_C. For the first expression this can be done by means of the well-known equations

$$\theta = \epsilon E \qquad \text{and} \qquad \lambda E = i \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

In this equation ϵ means the dielectric constant, λ the conductivity, and E the electric field. Through differentiation with respect to time t, we get the expression

$$\partial\theta/\partial t = (\epsilon/\lambda)\, \partial i/\partial t \quad (6)$$

which gives the desired relation between the dielectric and the conduction current. To eliminate I_C we use the fact that the resistance R and the capacity C are affected by the same potential drop, indicated by the letter U. R, C, and U are interrelated through the simple equations $U = IR$ and $U = Q/C$. Q is the charge of the capacity C. The variation of Q with respect to time, dQ/dt, is the current I_C and we obtain a relation between the current I_C through the capacity C, and the current I through the resistance R.

$$I_C = dQ/dt = C\, dU/dt = CR\, dI/dt \quad (7)$$

By means of (4), (6), and (7) we obtain the differential equation

$$CR\, dI/dt \quad I = [(\epsilon/\lambda)\, \partial i/\partial t + i]\, F \quad (8)$$

The expression $T = CR$ is the time constant of our input circuit. The expression $\theta = \epsilon/\lambda$ is the well-known time constant of air. Eq. (8) can be solved without difficulties and we obtain

$$I = F\,[Ae^{-t/T} + (\theta/T)\, i + (1/T)\,(1 - \theta/T)\, e^{-t/T} \int_0^t ie^{t'/T} dt'] \quad (9)$$

At first sight, (9) appears to be rather complicated; we have to consider, however, that this equation is of general validity, since any function can be introduced for the air-earth current i. Even without specifying the function for i, important conclusions can be drawn from this equation. The first term of the right side with the integration constant A determines the transient response. It will decay with increasing time and therefore it does not have to be discussed any further. The equation, thus, assumes the simplified form

$$I = F\,[(\theta/T)\, i + (1/T)\,(1 - \theta/T)\, e^{-t/T} \int_0^t ie^{t'/T} dt'] \quad (10)$$

The last term of the right side of (10) will be zero for the case $\theta = T$; that is, it will be zero if the time constant of the input circuit is equal to the time constant of the air. Then we obtain from (10)

$$I = i\, F \quad (11)$$

In this state the entire air-earth current picked up by the plate will go through the measuring resistance, whereas, all of the influence currents are deviated to ground through shunted capacity C. For example, we have to shunt the high ohm resistance of 10^{11} ohm to a parallel coupling of a capacity of about 9000 $\mu\mu$F in the case where the time constant of the air is about 15 minutes or 900 seconds. This shunting capacity is not, as heretofore, to be interpreted as damping capacity which more or less neutralizes the influence charges, but it has to be interpreted as balancing capacity by which we match the input of the measuring instrument to the atmospheric electrical circuit. This capacity is necessary to the correct balance by which we obtain not only an approximate but an exact registration of the air-earth current for all frequencies from zero to infinity. Variation from the fastest changes of the air-earth current, such as occurring during lightning discharges, down to the slowest diurnal variations is not only theoretically possible but has been practically carried out at the Meteorological Observatory at Aachen for quite some time.

If we choose to make the input capacity C smaller than is necessary for balancing, so a part of the influence current flows through the high resistance the circuit registers the well-known violent disturbances. If we choose to make the input capacity C larger than is necessary for balancing, a part of the air-earth current will be needed to charge the capacity. In this case the capacity C acts as a damping condenser and smooths out the fluctuations of the air-earth current. Both cases are of practical importance.

The first case, where the input capacity is too small, mismatching is suitable for recording the short-period current variations. This is again a measure for the exchange in the atmosphere which is normally difficult to record by other measuring devices.

The second case, where the input capacity is too large, mismatching is suitable for recording long-period current variations. For instance, in the investigation of the correlation between single weather periods and air-earth currents these long period current variations often occur.

We utilize (10) for investigation of mismatching by different frequencies of air-earth currents. The integral in (10) can be easily solved if we introduce the air-earth currents as sinusoidal alternating current.

$$i = i_0 e^{j\omega t} \quad \ldots \quad (12)$$

j = root of minus one, signifies the imaginary unit, and ω signifies the angular frequency. Substituting (12) in (10) we obtain the following expression

$$I = [(1 + j\omega\theta)/(1 + j\omega T)]\, iF \quad \ldots \quad (13)$$

If $\omega\theta$ and ωT are small in comparison with unity, that is, the duration of the current variation is great in comparison with θ and T, we can neglect the terms $j\omega\theta$ and $j\omega T$ compared to unity. We obtain again the single equation $I = i\,F$. If, however, the duration period of variation is small then we obtain approximately $I = (\theta/T)\, i\, F$.

If the ratio θ/T is larger or smaller than unity, then the measured current I will be larger or smaller than the air-earth current.

In closing I would like to show that (13) can, in a simple manner, be derived from the circuit diagram with the help of Ohm's law. Hereby, the main point is that we are able to interpret the dielectric constant ϵ as the capacity of the unit volume. We can do this with the same correctness as we interpret the conductivity λ as specific conductivity of the unit volume of air. We can show that best by a comparison of the definition equation. The conductance L of a square with the cross section F and the height h is given by the expression $L = \lambda F/h$, if λ is the specific conductivity. The capacity C of the same square is given by the well-known equation $C = \epsilon F/h$.

From these equations we obtain the specific conductivity as $\lambda = L\,h/F$ and the specific capacity as $\epsilon = C\,h/F$. The analogy of both formulas speaks for itself. ϵ has the dimension of a specific capacity, namely farad/m. This is an analog to the dimension of the specific conductivity mho/m. Since ϵ fulfills in addition all calculation rules which are derived for calculating capacities in electrical circuits, we can therefore interpret ϵ as capacity in our circuit diagram. Besides the presently used symbols we introduce for the current through the capacity ϵ the symbol i_ϵ. The current i_ϵ is identical to the Maxwell dielectric current or influence current density. In the manner we derived (4) we can now in a similar manner derive from the circuit diagram the following equation (Kirchhoffs law)

$$(i + i_\epsilon)\, F = I + I_C \quad \ldots \quad (14)$$

Now we have to eliminate from (14) the expression i_ϵ and I_C. Since the potential drop across r and ϵ must be equal, we obtain on the basis of the Ohm law $ir = (1/j\omega\epsilon)\, i_\epsilon$. In the same manner we obtain for the input circuit $IR = (1/j\omega C)\, I_c$. And from this get

$$i_\epsilon = ij\omega r\epsilon \qquad \text{and} \qquad I_C = Ij\omega RC \quad \ldots \quad (15)$$

Taking into consideration that $r\epsilon = \epsilon/\lambda = \theta$ and $RC = T$, so we derive from (14) and (15)

$$iF\,(1 + j\omega\theta) = I\,(1 + j\omega T)$$

or also

$$I = (1 + j\omega\theta)/(1 + j\omega T)\ i\,F \qquad (13)$$

We thus obtain the same result as we have derived above by the integration of Maxwell's equation.

This method of matching the input of our measuring instruments with the atmospheric-electric circuit by means of shunting an accurate capacity is simple to apply from a technical viewpoint. As mentioned before, this method has proven its value by the registration of air-earth current at the Meteorological Observatory in Aachen. This method has worked excellently in registering the air-earth current during lightning discharges, thunder clouds and fair weather. I hope that this method will help other atmospheric electricity research stations to overcome the difficulties encountered in registering the air-earth current.

A PROGRAM OF SIMULTANEOUS MEASUREMENT OF AIR-EARTH CURRENT DENSITY

R. E. Holzer

Institute of Geophysics
University of California, Los Angeles, California

Abstract--A program of simultaneous measurement of air-earth current density at remote stations with the purpose of distinguishing local and world-wide atmospheric electrical effects is described. Mountain stations are found to be superior to low-level land stations because local meteorological disturbances are smaller and more consistent. An investigation of the characteristics of Palomar Mountain has been made through simultaneous surface and free-air measurements. Two principal systematic local effects have been observed at Palomar. An exchange layer which develops in mid-morning and disappears near sundown lowers the air-earth current through an increase of atmospheric resistance over the mountain. It is found that the variation of the air-earth current to the mountain during the night hours is similar to corresponding variation in the air-earth current over the oceans. However, when correction for the variable resistance of the exchange layer during the daylight hours is made, the ratio of the air-earth current at Palomar to the air-earth current over the oceans is higher than at night. Possible causes of the rise of the air-earth conduction current during the day are suggested.

During periods of fair weather the air-earth current density is controlled in part by the potential difference between the Earth and high atmosphere and in part by local meteorological conditions. At land stations, the world-wide and local controls frequently produce variations of comparable magnitude thus making air-earth current records difficult to interpret. Even over the sea, local disturbances exist but the fact that these disturbances are random in time makes possible the use of averaging techniques to accentuate the world-wide effect and to minimize local disturbance. At present our knowledge of the character of the world-wide control pattern rests largely upon the mean diurnal variation of the potential gradient at sea for each of the four seasons.

It would clearly be desirable to have a better measure of the diurnal pattern of the potential difference V between the Earth and high atmosphere for shorter intervals of time so that one could assess its value as index in global problems of meteorology. A better measure of the world-wide control would also find use in simplifying the analysis of the relation between certain local meteorological conditions and atmospheric electrical measurements.

In 1950 we undertook a systematic search for better observing stations where the characteristic magnitude of local disturbance was small and possibly calculable. It was expected that if such stations could be found, simultaneous measurement at two or three such stations would provide a satisfactory measure of the mean diurnal variation of V for periods of a few days rather than for a season.

In the course of the project, measurements have been made at some forty land stations in California and on islands in the Pacific Ocean. Extended measurements have been made at about 15 of these land stations. The observing sites have ranged in elevation from sea level to 4000 m and have been located in several climatic regimes. In addition, measurements of about five months duration have been made over the Pacific Ocean between 170°E and 120°W longitude and between 35°N and 20°S latitude.

SCHILLING [1955] discusses results of one phase of the program and RUTTENBERG [1955] describes the sea measurements in the following paper. This paper will be confined to selected portions of the land measurements.

The air-earth conduction current density was computed as the product of potential gradient and conductivity. The potential gradient was measured continuously by both field mills and radioactive collectors with appropriate electronic circuits and Esterline-Angus recorders. The conductivity was measured continuously with a modified Gerdien-type instrument used in conjunction with a vibrating reed electrometer and pen recorder. While most of the measurements have been made in this way, instruments for measuring air-earth current directly have been built and used in the field. In principle the instruments are similar to that described by KASEMIR [1951].

The preliminary test of stations usually consisted of measurement of the vertical conduction current density for four consecutive days of fair weather simultaneously at two stations. Figure 1 is a representative sample of tests at four stations in February, 1952. West Los Angeles and Sage

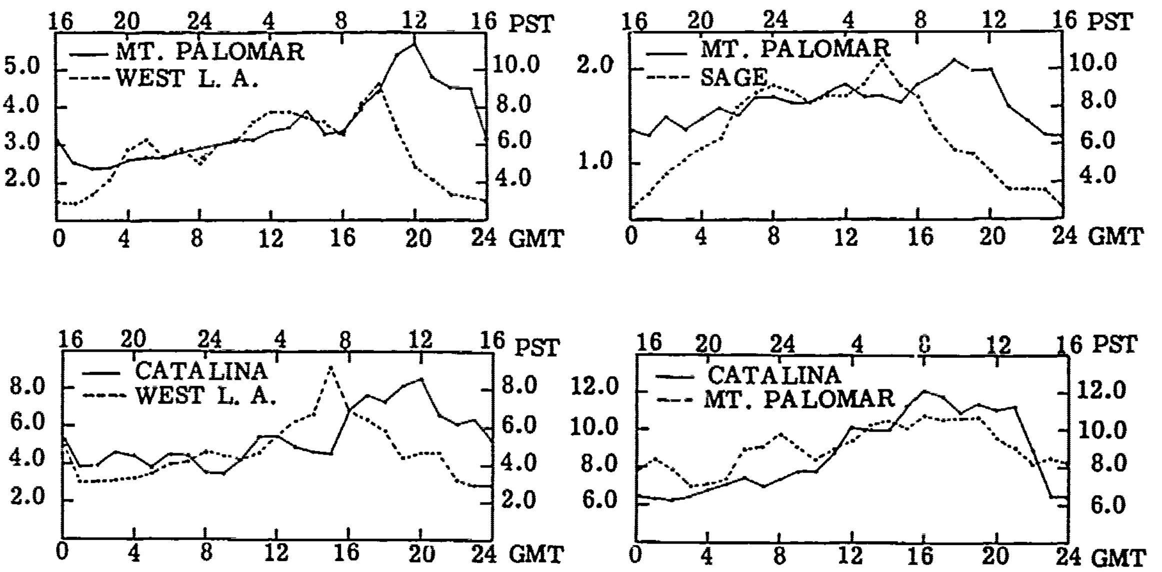


Fig. 1--Diurnal variation of air-earth current density at pairs of stations in Southern California, 1952 (amp/m^{-2} $\times$ 10^{-12})

are low level stations, the former on the coastal plain and the latter in a semi-arid region away from the coast. Palomar Mountain is at 1700 m elevation and 50 km from the ocean while the Santa Catalina station is at 500 m altitude on an island 35 km off shore. At most of the stations the trend of the air-earth current density i is very similar during the night. During the daylight hours i at the low level stations falls significantly relative to the values at either Palomar or Santa Catalina Island. This is consistent with the vertical development of the exchange layer accompanying surface heating. The Palomar and Santa Catalina diurnal curves show the greatest similarity in shape and both resemble the dirunal potential gradient curves at sea for the winter season. In general the stations at the tops of the higher mountains proved most satisfactory, as expected for several reasons. This result appears to be in agreement with some recent work of ISRAEL [1955] on mountain stations in Europe.

Figure 2 shows the measurement of i at Palomar Mountain and White Mountain 500 km north of Palomar. The elevation of the White Mountain station was about 3300 m. The records are for three weeks in June, 1952 and represent 20 days recording at Palomar and (due to weather and instrumental difficulties) only five days on White Mountain. The mean curves are strikingly similar in trend, and indicate that persistent features of the local meteorological control are similar in amplitude and phase at the two stations.

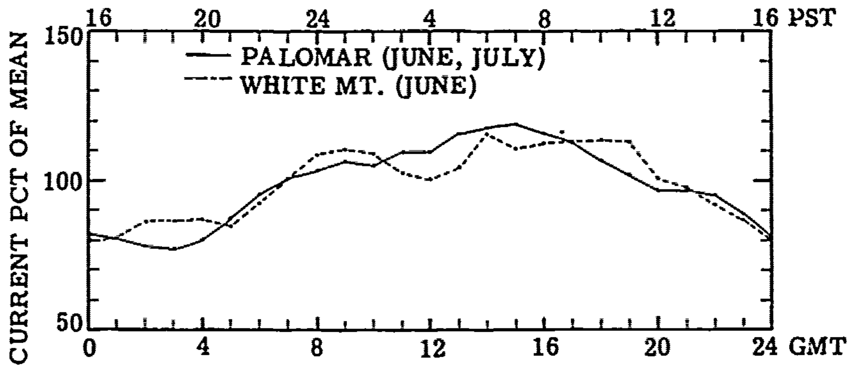


Fig. 2--Diurnal variation of air-earth current density at mountain stations at same longitude, 1952

In the summer of 1953 two types of test were undertaken: (1) simultaneous ground and airplane tests in the vicinity of Palomar Mountain, and (2) simultaneous measurements on White Mountain and Haleakala, a volcanic peak in the Hawaiian Islands. Time permits only the description of the first of these tests which was a joint project carried out by the Geophysical Research Directorate of the Air Force Cambridge Research Center and the University of California. The airplane measurements were made by the Geophysical Research Directorate under the direction of Mrs. Rita Sagalyn and her colleagues. The basic plan of the test consisted in continuous measurement of i at three stations, two on level areas within 30 km of Palomar and one on top of the mountain. The airplane equipped to measure conductivity as well as large and small-ion density and meteorological parameters circled the stations at constantly increasing or decreasing altitude. The maximum altitude of the plane usually 3000 to 4000 m was determined by the level at which the conductivity became the same over each station. It was possible from the plane measurements to compute the resistance of an atmospheric column over the station to 3000 m. During the three week period of observation ten flights, each of several hours duration, were made. Because of meteorological conditions results were satisfactory for only two of the ground stations, Palomar and Lake Henshaw at 1700 and 800 m, respectively. Figure 3 shows the mean diurnal variation of the resistance of

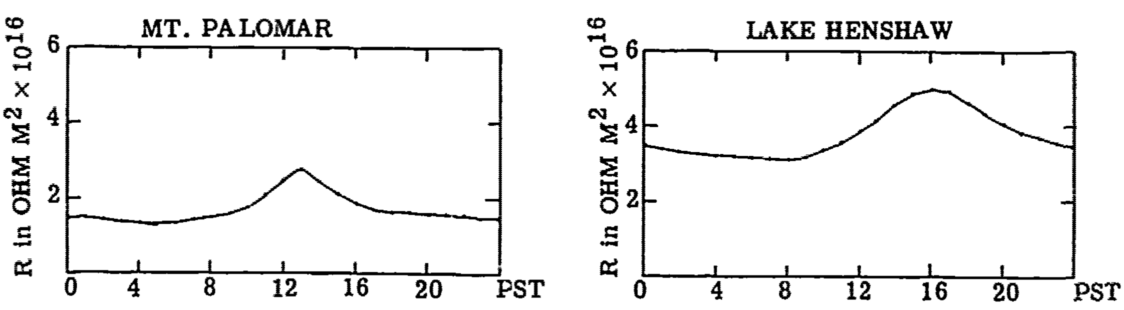


Fig. 3--Diurnal oscillation of columnar resistance

the atmospheric columns over Palomar and Lake Henshaw from the surface to 3000 m. The minimum resistance was found near dawn, while the maximum occurred shortly after noon for Palomar and about 16 h local time at Lake Henshaw. Lake Henshaw was found to be in the dense-particle layer at all times while Palomar was out of the particle layer during the late evening hours and

until two or three hours after sunrise. In attempting to compute the potential difference between Palomar and the high atmosphere, it was assumed that the resistance above 3000 m was the same as computed by GISH and SHERMAN [1936]. However, before using the computed oolumnar resistance (not strictly applicable to mountain measurements) it was necessary to make an empirical correction for the convergence of the current to the mountain top by comparison of the Palomar and Lake Henshaw measurements. Figure 4 shows the computed mean diurnal variation potential

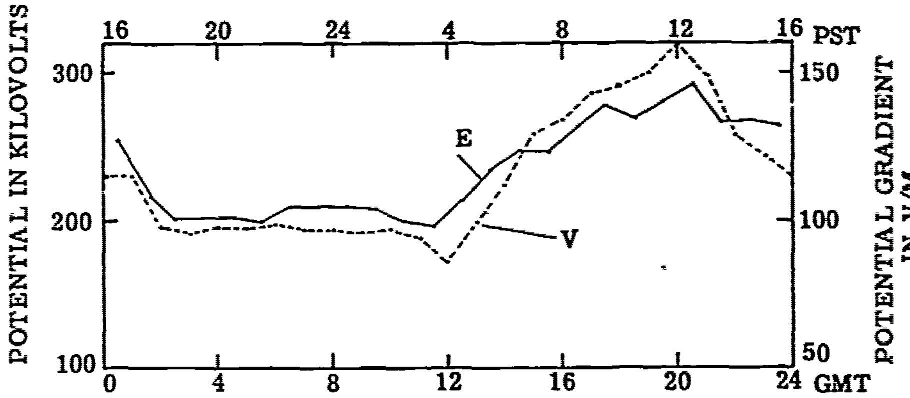


Fig. 4--Comparison of computed value of V for Mt. Palomar, June, 1953, and measured potential gradient at sea (Carnegie)

of the upper atmosphere over Palomar for June, 1953. On the assumption that the potential gradient E at sea is proportional to the same potential difference between the Earth and high atmosphere, the curve of E taken on Cruise VII of the Carnegie for May, June, and July is shown on the same diagram. Again the agreement is very striking. It indicates that the variation in the diurnal resistance of the atmosphere over Palomar represents the princ:pal persistent local effect (about 20 pct of the mean).

To determine whether there were any striking local peculiarities in the site chosen for the test we placed potential gradient instruments at another point on Palomar Mountain and on Table Mountain about 150 km to the north. Figure 5 shows the mean diurnal variation of the gradient at three

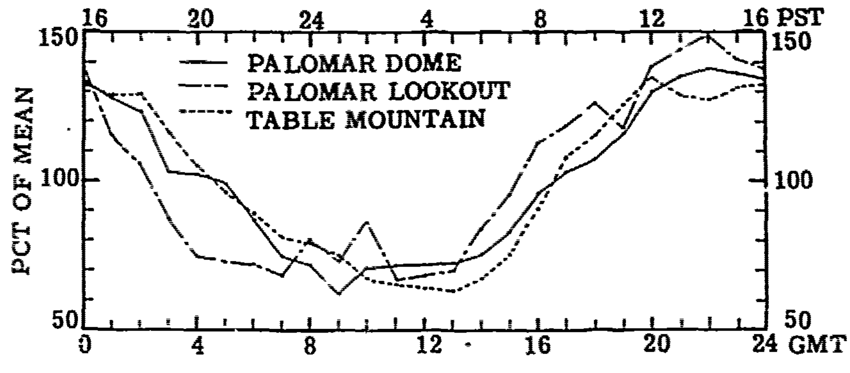


Fig. 5--Comparison of potential gradient at three mountain stations, 1953

stations during the test. The similarity is obvious and there is reason to believe that air-earth current records would have been in even better agreement. The observations at Palomar appear to be characteristic of other mountains in the region.

Another local effect is apparent in the data from Palomar. After the curves in Figure 4 have remained essentially parallel during the night the curve for Palomar begins to rise more rapidly than the ocean curve after local sunrise at Palomar (05 h PST). It exceeds the ocean curve by the maximum amount at local noon. A similar effect, a rise of air-earth conduction current after sunrise, has been found at nearly all other stations at which we have made measurements. The apparent rise of V above the sea curve is presumably due either to the development of an EMF in the atmosphere, to the fall of the resistance of the column, or to the development of a convection current in the first few meters above the surface. We have been making some tests to determine whether the development of a convection current near the instrument will cause the conduction current to exceed the total air-earth current. These tests have not been carried out over a sufficiently long period to permit any final conclusions. If these tests fail to produce an explanation for the observations in the surface layer of the atmosphere, one will be forced to look high in the atmosphere possibly to a layer of particles around 80 km which is out of the highly ionized region of the atmosphere at night but within the D region during the day.

The present series of experiments on mountains will be carried on during the next six months when it is hoped that a few of the remaining problems will find some solution.

I wish to express my appreciation for the cooperation of G. F. Schilling, S. Ruttenberg, L. G. Smith, and others who were largely responsible for conducting the tests I have described. The research reported in this paper was made possible through the support and sponsorship extended by the Geophysical Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under Contract No. AF19(122)-254.

References

GISH, O. H., and K. L. SHERMAN, Electrical conductivity in the atmosphere to an altitude of 22 kilometers, Nat. Geog. Soc., Cont. Tech. Papers, Stratosphere Ser. 2, pp. 94-116, 1936.

ISRAËL, H., Synoptical researches on atmospheric electricity, Proc. Conference on Atmospheric Electricity, May 1954, pp. 11-20, 1955.

KASEMIR, H. W., An apparatus for simultaneous registration of potential gradient and air-earth currents, J. Atmos. Terr. Physics, v. 2, pp. 32-37, 1951.

RUTTENBERG, S., and R. E. HOLZER, Atmospheric electrical measurements in the Pacific Ocean, Proc. Conference on Atmospheric Electricity, May 1954, Air Force Camb. Res. Center, pp. 101-108, 1955.

SCHILLING, G. F., On the variation of electrical conductivity of air with elevation, Proc. Conference on Atmospheric Electricity, May 1954, pp. 53-58, 1955.

ATMOSPHERIC ELECTRICAL MEASUREMENTS IN THE PACIFIC OCEAN

S. Ruttenberg and R. E. Holzer

Institute of Geophysics
University of California, Los Angeles, California

Abstract--An atmospheric-electric research program was conducted during Operation Capricorn, a five month's geophysical marine expedition to the central Pacific undertaken by the Scripps Institution of Oceanography of the University of California. Continuous records of the potential gradient and positive conductivity were obtained from a field-mill instrument and a Gerdien-type conductivity apparatus, respectively. Mean monthly values and diurnal curves of both variables are presented. The seasonal mean diurnal curves of the potential gradient on Operation Capricorn are in striking agreement with the corresponding seasonal mean curve for Cruise VII of the *Carnegie* indicating no important secular change in the diurnal seasonal pattern. Some evidence is found for a small local diurnal effect superimposed on the global fluctuation of potential gradient.

Introduction--At the beginning of the program of simultaneous atmospheric electrical measurements described in the previous paper [HOLZER, 1955], it was recognized that new measurements at sea on the scale of the measurements made on the *Carnegie* [TORRESON, GISH, PARKINSON, and WAIT, 1946] would be highly desirable. Two preliminary cruises in the eastern Pacific Ocean near California provided experience in sea measurements and an opportunity to test the measuring equipment. Due to unfavorable weather, the first records were of little value in determining the global diurnal variation of the potential gradient. The first opportunity for extensive sea measurements far from continents was provided by Operation Capricorn, conducted by the Scripps Institution of Oceanography of the University of California. While the expedition was primarily concerned with submarine geological measurements, programs in oceanography, tropical meteorology, and atmospheric electricity were included.

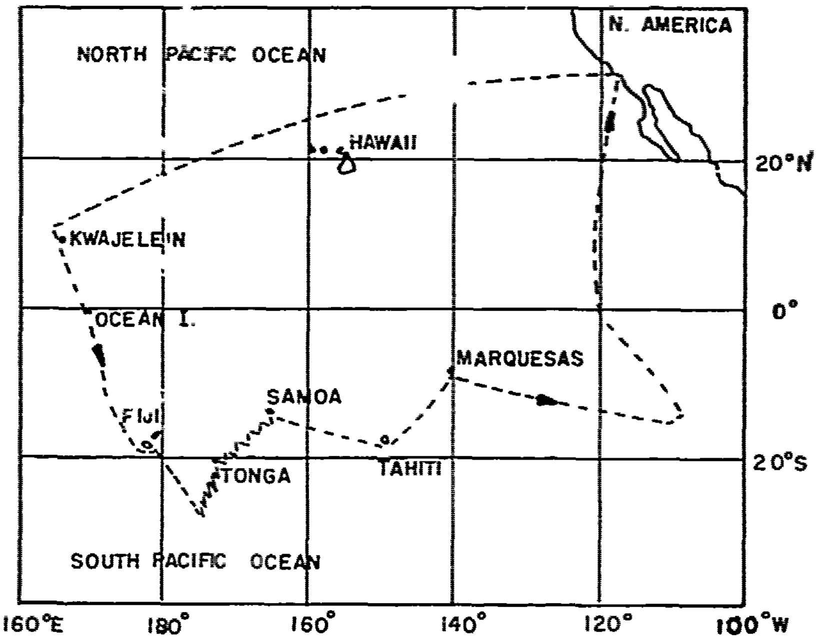


Fig. 1--Track of R/V *Horizon* during Operation Capricorn
Scripps Institution of Oceanography

Figure 1 shows the course of the expedition which left San Diego on September 26, 1952, proceeded west through the central Pacific to the Marshall Islands and returned to San Diego on February 25, 1953. During the main part of the expedition from Kwajelein to San Diego the weather was generally fair with only two short periods of complete overcast. Occasional periods of unsettled weather, involving local squalls of less than two hours duration, represented only a small fraction of the total observing period. Records from these periods of disturbed weather were eliminated in the analysis. No other selection of data on the basis of weather was made. Approximately two-thirds of the steaming time from November to February provided good records. The remaining one-third of the total period failed to provide satisfactory records for one of the following reasons: ship not steaming during oceanographic operations, ship in port, occasional instrument failures, and disturbed weather, mentioned above.

Instrumentation--During the preliminary cruises it was found that the field-mill type of potential-gradient instrument was very satisfactory for sea measurements and when properly placed, not affected by salt spray. In the field-mill instrument three stationary plates were connected to ground through a two megohm resistor. The rotation of a grounded shield above the stationary plates generated an alternating current. Polarity of the field indication was determined by applying a steady bias field over one of the plates. The signal was amplified, rectified, and recorded on an Esterline-Angus strip recorder. The conductivity instrument was of the Gerdien type. The current to the central cylinder was measured by a vibrating reed electrometer and continuously recorded on a second Esterline-Angus strip recorder. The conductivity instrument was calibrated by Smith [1953] and checked by him with the conductivity apparatus used at the Carnegie Institution Magnetic Observatory at Tucson.

Both the field-mill potential-gradient instrument and the conductivity instrument were mounted permanently on the R/V Horizon, one of the two vessels in the expedition. The instrument location on the flying bridge, on top of the wheel house and forward of the main mast and exhaust stacks, was chosen because measurements were to be made while the ship was underway. The location had the further advantage that it was undisturbed by any of the ship's normal operations. The field mill mounted immediately above the conductivity apparatus was ten meters above the sea surface. The intake of the conductivity tube was exposed to the direct sea wind and received a minimum of atmospheric contamination from the ship.

A second, portable potential-gradient instrument consisted of a radioactive collector, DC electrometer, and recorder. This instrument was checked against the field mill aboard ship and was found to exhibit proportional readings even including small disturbances of a few seconds duration. During island stops the second potential-gradient instrument was taken ashore for comparative measurements when weather permitted.

On the Marshall Islands, the radioactive collector instrument was set up with a stretched wire one meter above the beach on the lagoon side of a small islet while the Horizon was anchored a few hundred meters off shore. Several hours of records were obtained simultaneously on the island and ship board with favorable wind and good weather. These data were used for obtaining a reduction factor for the potential gradient instrument on the ship.

Results and discussion--The monthly mean values of the potential gradient (with reduction factor applied), positive conductivity, and air-earth current density for all months from October to February, inclusive, are presented in Table 1. In each case the monthly mean values are computed from the hourly mean values for undisturbed periods.

The positive conductivity was measured almost exclusively because frequent checks for short intervals indicated the essential equality of the positive and negative conductivity (within less than ten per cent) regardless of the value of the potential gradient. The probable reason for the consistency of the approximate equality of the two polar conductivities is that the air sampled was taken at nine meters above the sea surface, usually with a stiff breeze of 15 to 20 knots blowing. The air-earth current density was accordingly calculated as the product of potential gradient and twice the positive conductivity.

Table 1--Monthly mean values of positive conductivity, potential gradient, and air-earth current density

Date	Positive conductivity	Potential gradient	Air-earth current density
	$ohm^{-1}m^{-1}$	volts/m	amp/m^2
Oct. 7, 1952	1.58×10^{-14}	108.4	2.95×10^{-12}
Nov. 3-7, 1952	2.08×10^{-14}	100.4	4.18×10^{-12}
Dec. 22, 1952	1.68×10^{-14}	123.1	4.18×10^{-12}
Jan. 18, 1953	1.45×10^{-14}	98.9	2.95×10^{-12}
Feb. 19, 1953	1.19×10^{-14}	107.8	2.55×10^{-12}

The monthly means of the diurnal variation of the potential gradient are shown as a function of Greenwich Civil Time in Figure 2. All of the monthly curves exhibit a single daily oscillation

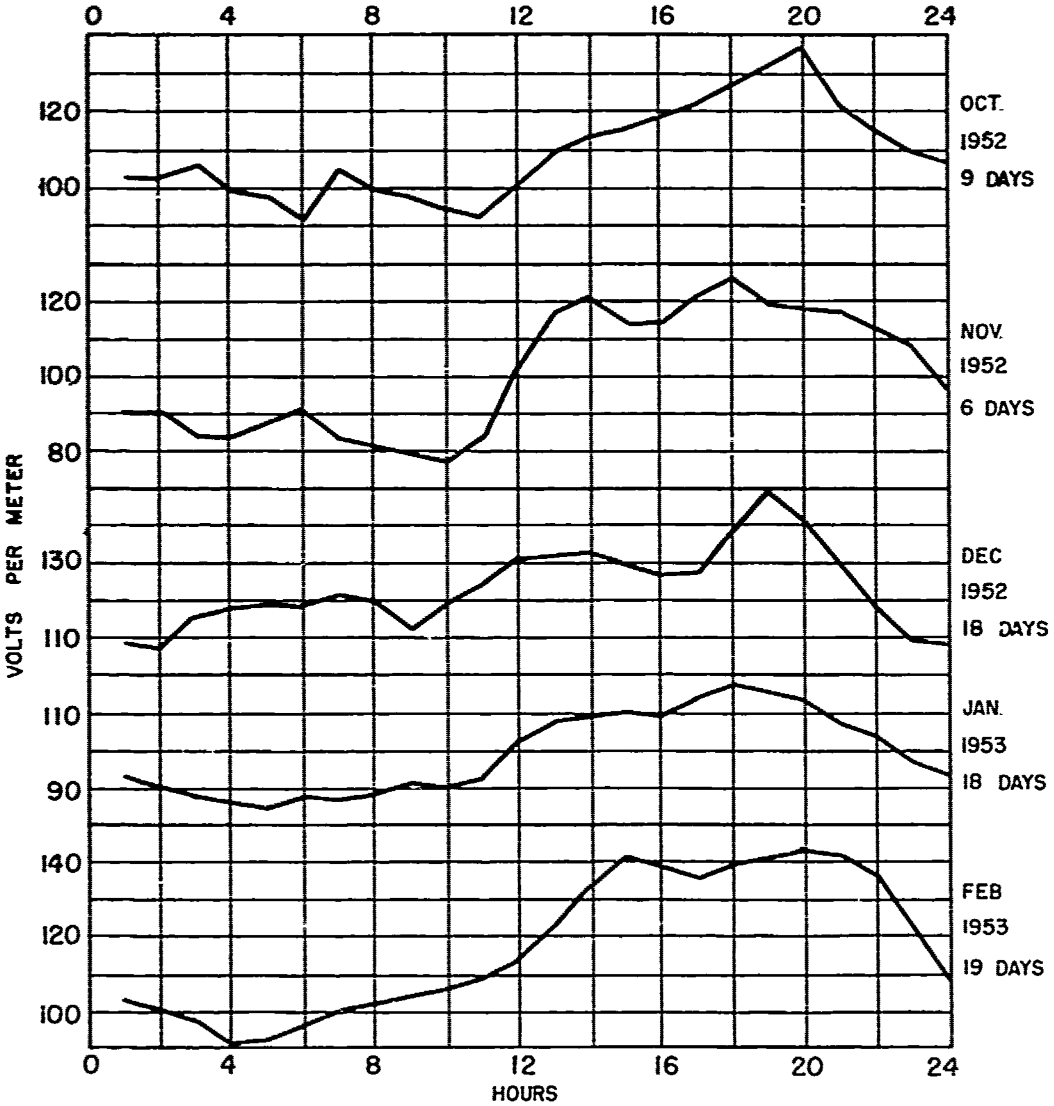


Fig. 2--Reduced values of the potential gradient in volts/meter taken aboard the R/V. Horizon in the central Pacific Ocean, Oct. 1952-Feb. 1953

approximately in phase although, as may be expected, individual differences are apparent. The monthly mean values of the potential gradient range from 123.1 to 98.9 volts/m and the mean oscillation (ratio of the difference between maximum and minimum values to the mean) range from 30 pct in January to 45 pct in February. The range of variation in the daily records was even larger.

In order to compare the results of Operation Capricorn with those of the Carnegie, a seasonal mean curve for the months of November, December, and January was prepared. Data from Cruise VII of the Carnegie for November, 1928, to January, 1929, were used because more individual days of observation were available for computing the seasonal mean than in any of the previous cruises. The two seasonal mean curves are presented in Figure 3. In spite of the difference in absolute

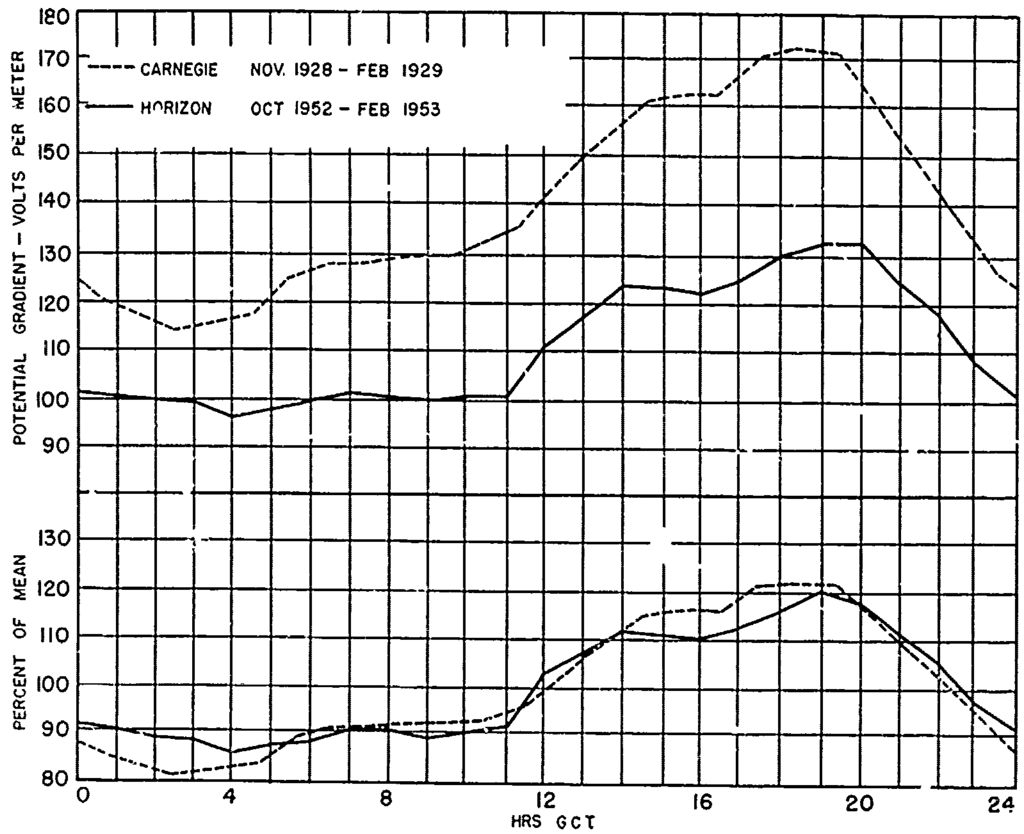


Fig. 3--Potential gradient means from the Pacific, Carnegie, Cruise VII, 1928-1929, and R/V Horizon, Operation Capricorn 1952-1953

magnitude of the potential gradient in the two cases, the shapes of the curves are remarkable similar. The similarity in shape is best illustrated when the curves are plotted as per cent of the mean value of the potential gradient in each case. The correlation coefficient between the per cent of mean data for the Carnegie and the Horizon is a surprising 0.97.

It is of particular interest to note that the observations on the Carnegie in 1928-29 were made in the eastern Pacific principally between 80° and 120°W longitude while the observations on the Horizon in 1952-53 were made between 120°W and 170°E longitude. The best agreement between the per cent of mean curves occurs during the part of the day when both ships were in the dark about 05 to 12h GCT. Sunrise occurs at an earlier hour at the Carnegie, and the Carnegie curve first rises above the Horizon curve. In the late afternoon hours for the Carnegie, about 23h GCT the Horizon curve becomes higher than that of the Carnegie and remains above until about sunset

at th orizon. Because there is no systematic fall in the conductivity corresponding to this relative . .e of the potential gradient the effect may be described as an apparent rise of the air-earth conduction current density during the local daylight hours.

The effect is small and based upon average data, hence a statistical analysis to determine its probable significance is required. The t test of the significance of the difference of the means of the two sets of data at any Greenwich hour was applied on the assumption that the standard deviation of the theoretical population is adequately represented by the standard deviations of the two hourly samples. For the three hours that the per cent of mean curves show the largest separation, the probabilities that these differences were due to sampling errors are 0.16, 0.08, and 0.22, respectively. These values are larger than the 0.05 commonly used by statisticians as a criterion that the differences of the means are significant. However, the values are sufficiently small that the possibility of a small persistent local effect at sea cannot be dismissed. A local effect of the same character but much larger in magnitude, observed on mountain stations and other land stations was described by HOLZER [1955].

The seasonal mean curves of the air-earth conduction current density for the Carnegie and the Horizon are shown in Figure 4. The curves exhibit similar phase although the oscillation of the Carnegie curve is larger. The correlation coefficient for the two sets of data is 0.94. As expected,

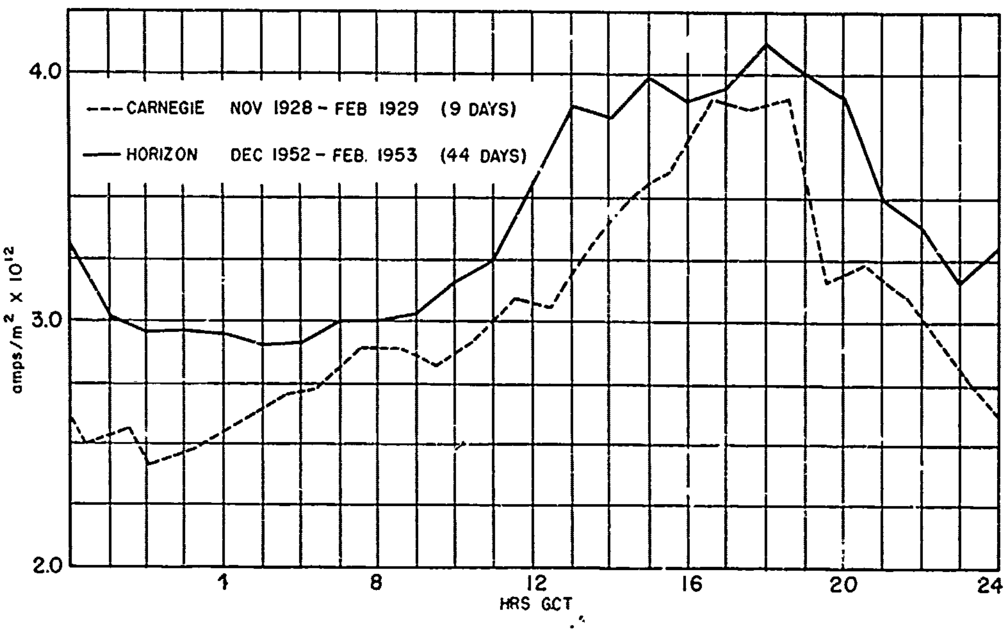


Fig. 4--Computed values of air-earth current density in the Pacific Ocean, Carnegie 1928-1929, and Horizon 1952-1953

when the surface conductivity varies only slightly the potential gradient and air-earth current curves have essentially the same characteristics. The mean value of the air-earth current density for the months of November, December, and January is 3.0×10^{-12} amp/m^2 for Cruise VII of the Carnegie and 3.4×10^{-12} amp/m^2 for the Horizon. The difference may possibly be due to small secular changes in thunderstorm activity as suggested by HOGG [1955]. However, the present data are not conclusive in this matter since uncertainties in determining the potential gradient reduction factors for the Carnegie and Horizon as well as in the absolute calibrations of the conductivity instruments could account for a difference of ± 20 pct in the absolute values.

Since a number of authors have referred to the sea as the most favorable place for atmospheric electrical measurements, free of persistent local disturbance, it is appropriate to examine some of the actual records. Figure 5 is a photographic reproduction of the potential gradient and positive conductivity records obtained in January, 1953, on an ideal doldrums day. The wind velocity with respect to the sea surface was zero; the sea surface, glassy; the sky, almost completely clear; and the ship was sailing a straight and steady course. The potential gradient executed an oscillation of

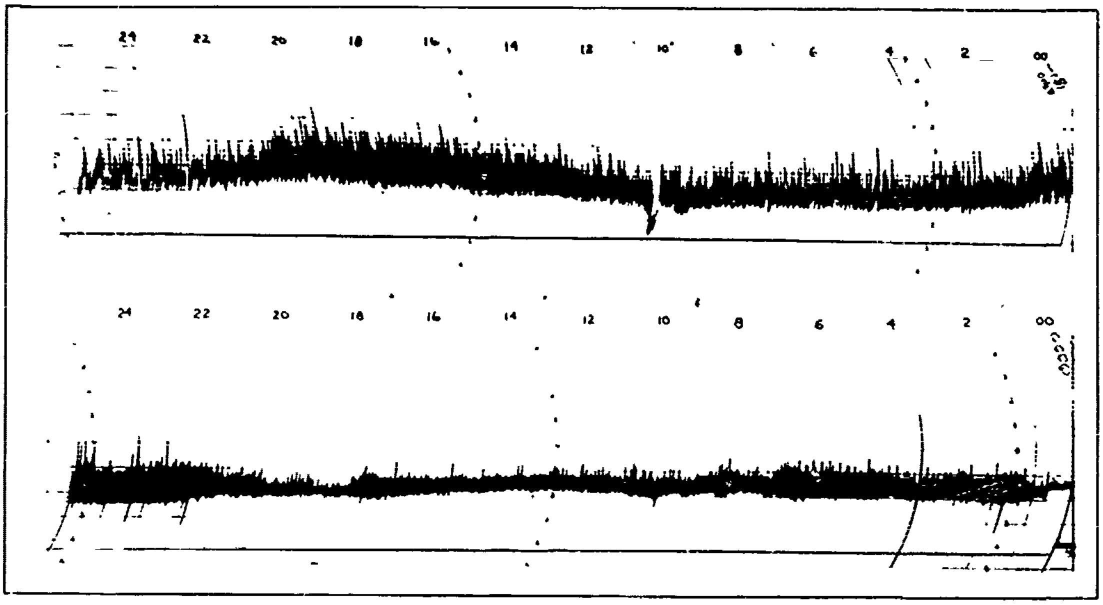


Fig. 5--Photograph of potential gradient (upper) and positive conductivity (lower), undisturbed day

somewhat more than average amplitude and with a suggestion of a double minimum. The variation of the positive conductivity of about 15 pct during the day is somewhat larger than anticipated and certainly much larger than the average daily variation. Further, apparently even under nearly ideal sea conditions both the potential gradient and the conductivity exhibit almost continuous short term noise-like fluctuations. The amplitude of the noise in the conductivity record is actually greater than that for a more nearly normal day as shown in Figure 6.

Figure 6 is a photograph of records taken on a more typical day: mostly clear with some scattered small cumulus and occasional moderate vertical development, some showers occasionally visible in the distance, wind 10 - 14 knots and sea moderate with occasional white caps. Although the gradient record still shows quite well the single diurnal oscillation many small disturbances in both records, due to normal cruise operations, are evident. At 01h 00m the ship slowed to a few knots for a dredge and net haul. As long as the ship maintained a forward motion of even only a few knots speed, the records are not much disturbed but as soon as the ship stopped and lay-to, at 02h 50m, the change in the records is quite obvious. Even though the wind vector was still from the bow of the ship the conductivity was depressed and quite disturbed while the gradient showed an increase. At 05h 00m motion was resumed and the records returned to normal. During the night the course was changed a few times in connection with another program and the corresponding changes in the records at 07h 45m, 08h 50m, 10h 15m, etc. are evident.

Conclusions--More continuous observations of potential gradient at sea have been obtained on the Horizon (42 days in the period November, 1952, through January, 1953) and on the Carnegie (34 days in the period November, 1928, through January, 1929) than in any other three months periods in the history of sea measurements. The striking agreement in the mean diurnal curves for these corresponding seasons 24 years apart indicates that there is no important secular change in the

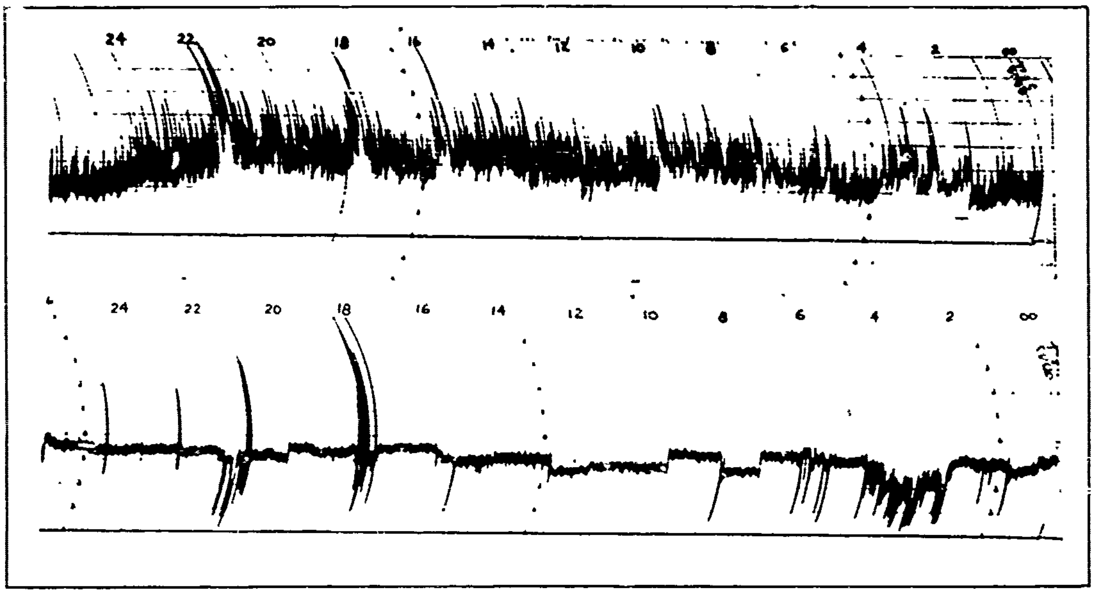


Fig. 6--Photograph of potential gradient (upper) and positive conductivity records, typical fair weather day

mean daily variation of the potential difference between the Earth and the highly conducting layers of the upper atmosphere when the means are computed for a season. These results justify the practice of workers in the field of atmospheric electricity who have compared seasonal mean daily variation of the atmospheric electrical parameters obtained at land stations with corresponding variations at sea observed many years earlier.

It must be emphasized, however, that there are important variations from one day to the next and also from month to month, as illustrated in Table 1 and Figure 2. Therefore, it cannot be concluded that the mean daily curves of the potential gradient for periods much shorter than a season will necessarily show the same constancy from one epoch to another.

The seasonal average of the potential gradient for the Horizon is lower than the seasonal average of the potential gradient for the Carnegie, however, the correspondingly higher value of the conductivity measurements on the Horizon bring the computed average air-earth current density into fair agreement with that for the Carnegie. Thus, it appears that there are no large secular changes in the mean values of air-earth current density. The limitation on the accuracy of the absolute measurements of gradient and conductivity precludes the possibility of drawing conclusions concerning small secular change in air-earth current density. There is no obvious explanation for the relatively large differences in the separate measurements of potential gradient and conductivity as observed on the Horizon and Carnegie.

There is a definite possibility of a persistent local diurnal effect at sea which produces a small increase in the air-earth conduction current density during the daylight hours. The present data do not suffice to determine whether such a cycle may be associated with local disturbance produced by the ship itself or whether it may be of more general character.

Finally, the persistently observed noise-like variations in both the potential gradient and conductivity even under apparently ideal conditions constitutes an interesting problem for further study. The effects are very probably related to the turbulence and small scale inhomogeneities of the lower atmosphere.

Acknowledgments--The research reported in this document has been sponsored in part by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, under contract number AF19(122)-254 and was made possible through the cooperation of the Scripps Institution of Oceanography of the University of California, La Jolla, California.

References

HOGG, A. R., A survey of air-earth current observations, Proc. Conference on Atmospheric Electricity, May 1954, Air Force Camb. Res. Center, pp. 86-90, 1955.

HOLZER, R. E., A program of simultaneous measurement of air-earth current density, Proc. Conference on Atmospheric Electricity, May 1954, Air Force Camb. Res. Center, pp. 96-100, 1955.

SMITH, L. G., On the calibration of conductivity meters, Rev. Sci. Instrum., v. 24, no. 10, p. 998, October, 1953.

TORRESON, O. W., O. H. GISH, W. C. PARKINSON, and G. R. WAIT, Scientific results of Cruise VII of the Carnegie 1928-29, Carnegie Inst. Pub. 568, 1946.

SOME RESULTS OF ATMOSPHERIC ELECTRICITY MEASUREMENTS ON THE GREENLAND ICECAP

P. Pluvinage

Expeditions Polaires Francaises et Faculte des Sciences de Strasbourg
Strasbourg, France

Abstract--Some measurements of the potential-gradient on the Greenland Icecap are reported. During fair weather, the values are a little higher than over oceans. With the data already published, one can compute an air-earth current density which is nearly the same as found by Dauvillier on the east coast, so that the maintenance of a state of equilibrium with a well-pronounced electrode effect is likely. In the presence of snow drift the values are very great, generally positive, and are correlative to the impact of ice particles on the insulated collector. One experiment shows that the true charge of the ice particles near the ground is very significant but negative. Therefore it is probable that the ice-metal friction constitutes the main agent of electrification of the insulated collector.

The scientific projects of the French Polar Expeditions 1948-51, led by P. E. Victor, included the study of some electrical properties of the air on the Greenland Icecap. Unlike the meteorological and seismic soundings research, this part of the program did not have the benefit of information acquired by previous expeditions. Nevertheless it is useful, for the sake of comparison, to recall that potential gradient and conductivity have been measured [DAUVILLIER, 1938] during the International Polar Year 1932-33 at the Scoresby Sound, on the east coast, and that, during the same time, very extensive studies of these and others parameters have been made [SHERMAN, 1937] at Fairbanks in Alaska in conditions similar, in some respects, to those of the coast of Greenland. Our attention will be directed here towards potential gradient, conductivity, and calculated air-earth current during summer. We shall quote later the results of Dauvillier and Sherman.

On the Greenland Icecap, the most accurate measurements have been made by P. Stahl during the campaign of 1951 with instruments improved from the experience acquired during the previous years. Concerning the conductivity, the results have already been published [PLUVINAGE and STAHL, 1953]. I recall that at the 'Station Centrale' (40° 38′ W, 70° 55′ N, 2994 m) very great values have been found for the ratio λ_+/λ_- and that they have been tentatively explained by the electrode effect. In 1951, Stahl noted that the ground was perfectly flat, mirror-like over great areas. The density of the surface snow is 0.33 according to measurements [SORGE, 1939] during Wegener's Expedition of 1930-31. A lower limit of its electric conductivity is given by 0.33 times the value for pure ice, that is 0.86×10^{-10} ohm^{-1} cm^{-1} so we may consider it as a conductor from an electrostatic point of view. With respect to the movements of the air, one may say that the circumstances are not at all appropriate to the formation of eddies. The possibility of a well pronounced stratification of the air is clearly shown by the diagrams of temperature drawn from measurements by G. Taylor (Fig. 1). The hypothesis of an effective electrode-effect is at least probable.

The measurements of potential gradient were performed with a device [LUTZ, 1937] which gives the absolute value directly. The Figure 2 is sufficiently explicit and no explanation is required. In fact the recording electrometer was the one used by LECOLAZET [1949] for his studies in a glider. It gives continuous registrations during nearly five hours and the speed of the film is rather high, 4 mm per minute. This speed was well adapted to the study of the effects of the snow drift. We shall first examine the fair weather values. Nine films have been selected for the Station Centrale. The potential gradient has been read every minute and the mean value calculated hour by hour. The main features are most often a great regularity and a very well defined hourly variation. The regularity is nearly the same as obtained by Lecolazet in his free air measurements in France. The perfect uniformity of conditions in both cases accounts for that. Table 1 summarizes the results and allows the comparison with Dauvillier's and Sherman's values.

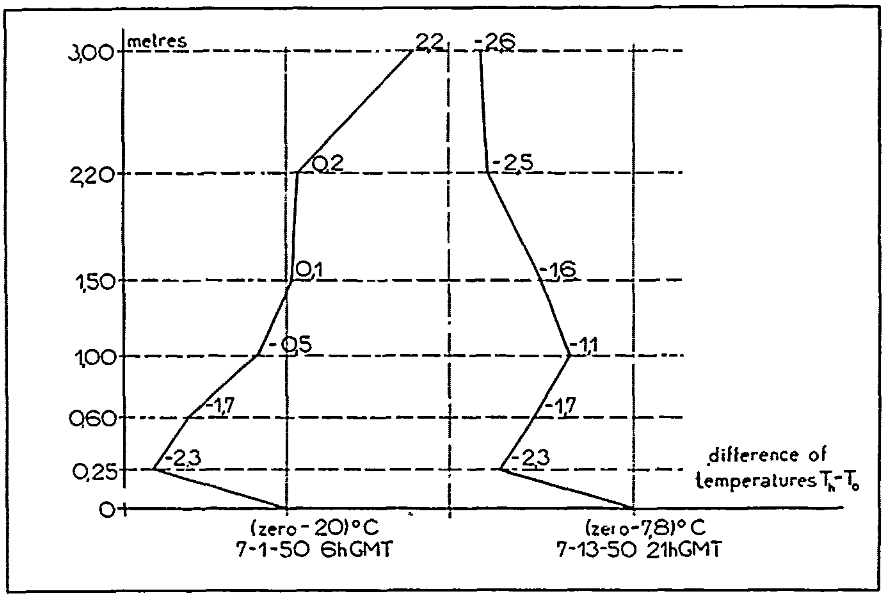


Fig. 1--Examples of stratification in the air above the surface of the Icecap (measured by G. Taylor)

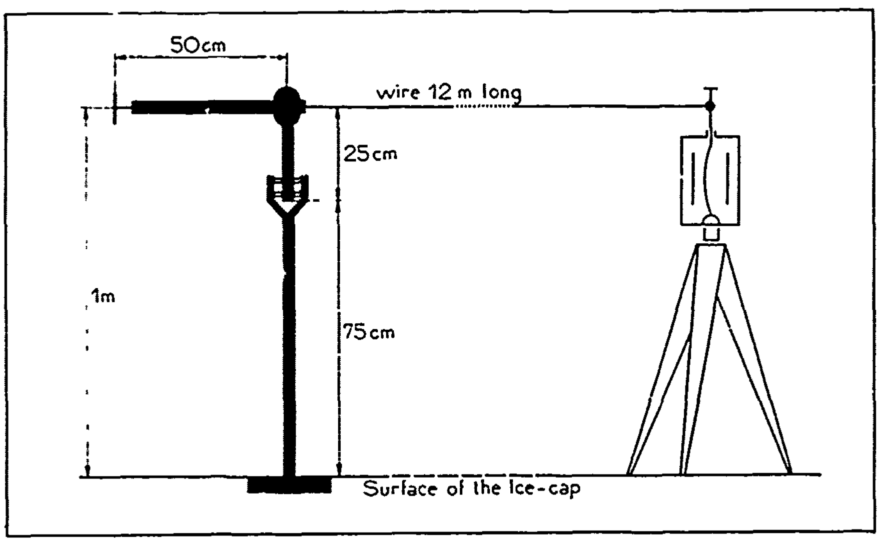


Fig. 2--Elevation of the installation

The general mean value of 138 V/m is somewhat greater than over oceans, and decisively greater than those measured by Dauvillier or Sherman. On the other hand, it has nothing in common with the free-air value at 3000 m above sea level, even if one takes into account the electrode effect. As for the comparison with the Dauvillier value, one may observe that the ratio of the potential gradients is roughly the inverse of the ratio of the total conductivities. Therefore, the calculated air-earth current is nearly the same at the Scoresby Sound and at the Station Centrale, where we found nine values ranging from 2.10 to 4.51 × 10^{-12} amp/m^2

Table 1--Comparison of results

Item		Scorebys Sound	Station Centrale	Fairbanks (selected days)
Mean potential gradient (v/m)		80	138	85.5
λ_+ (10^{-4} e s c g s units)				
	mean	1.79	1.72	1.60
	minimum	0.45	1.38	...
	maximum	2.94	2.89	...
λ_- (10^{-4} e s c g s units)				
	mean	1.53	0.61	1.30
	minimum	0.49	0.14	...
	maximum	3.08	1.55	...
i (10^{-12} amp. m^{-2})				
	mean	2.93	3.12	2.48
	minimum	0	2.10	...
	maximum	7.10	4.51	...

[a]Fog excluded

with a mean of 3.12×10^{-12} amp/m^2. It is not very different from the value deduced from the measurements by Sherman, so we can assume an approximate constancy of the air-earth current density over large areas in the Arctic. We may construct a coherent picture by assuming that a state of equilibrium is attained with a downwards current not depending on the height.

The smoothness of the registrations is destroyed when wind stirs up the ice particles from the surface of the Icecap. A layer of snow drift is then moving at the speed of the wind. Its thickness may range from a few centimeters up to ten meters and more. When the potential gradient apparatus is inside the layer, the potential reached by the insulated conductor is so high that, even with only $\pm$ 1.5 volt on the plates, the thread of the electrometer touches a plate, generally the negative one. This causes it to drop to zero, whereupon the charging commences again. This effect is, of course, correlated with the incoming of ice particles on the insulated conductor. The question that arises is whether it can be explained by the friction of ice on the collector or by a charge carried by the particles. Here we summarize some facts which may prove useful on solving this problem.

(1) Above a sufficiently thin layer of snow drift, it seems that the insulated conductor is not touched by the ice particles, and yet the mean value of the potential gradient is several times the fair-weather value. This fact is not explainable by a charge on the visible snow drift which would give no change in the mean field in presence of the Earth as a plane conductor. We shall assume in such cases that there are small unnoticed ice particles which accompany the lower and visible layer and come into contact with the insulated conductor. But that does not mean that a charge is not also present on the lower and main layer.

(2) Knowing the effective resistance, about 8.0×10^{10} ohms, of the radioactive collector, the surface exposed to the snow drift, about 200 cm^2, and the speed of the wind, say 10 m/sec, one may compute the charge produced by or bound to the ice particles in a cm^3. In a specially interesting observation at Nunatak Cecilia, near the east end of the Icecap, Stahl found a difference of nearly 400 V/m between the disturbed and fair-weather mean values above an irregular layer of snow drift whose maximum thickness was nearly 50 cm. We deduce that the charge produced by or attached to the conjectured invisible ice particles is as high as 1.5×10^5 elementary charges/cm^3.

(3) This same day, Stahl had the idea of placing the external part of the potential-gradient apparatus behind his sledge cabin, at the same distance of 12 m (Fig. 3). The insulated conductor was then sheltered from the snowdrift. Immediately the mean reading of the electrometer dropped to 35 V/m. The mean fair-weather value is somewhat less than at the Station Centrale, say 100 V/m.

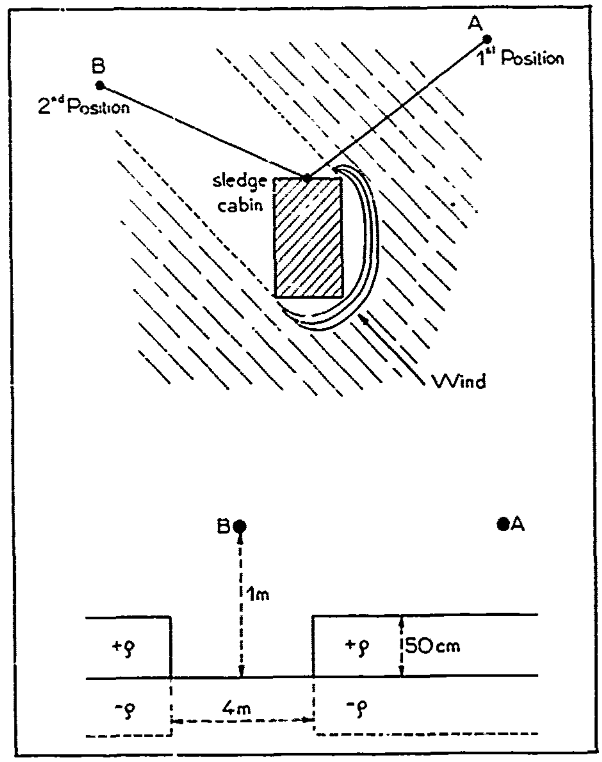


Fig. 3--Plan of the two positions of the collector with respect to the sledge cabin and diagram of the distribution of charges ($\rho > 0$)

We conclude that the charge outside the wake of the sledge cabin was negative and that, accompanied by its positive electric image, it compensated two-thirds of the normal charge of the earth. A rough calculation is possible by assuming that the visible layer of snow drift carries the main portion of the charge and that the wake of the sledge-cabin is a channel of rectangular cross-section, four meters wide and 0.5 m thick. The outer of magnitude of the charge density ρ is then 10^5 negative charges per cm^3.

(4) Therefore, the friction of the unnoticed ice particles against the insulated conductor, seems the only possible explanation of the high positive charge potential observed with the electrometer. But the weakness of this theory is that it is founded on only one experiment. I must also mention that one hour after the movement from the first to the second position, an inverse movement was performed but unfortunately the speed of the wind had decreased, the electric field had increased and no difference was found between the two positions.

References

DAUVILLIER, A., Année Pol. Internat. 1932-33, participation française, II, Gauthier Villars, 1938.

LECOLAZET, R., Nouvelles mesures du champ électrique atmosphérique en planeur, An. Géoph., v. 5, no. 1, pp. 84-86, 1949.

LUTZ, C. W., Geräte zur Messung und Aufzeichnung des luftelektrischen Spannungsgefälles, Gerl. Beit. zur Geophys., v. 31, no. 4, pp. 398-425, 1937.

PLUVINAGE, P., and P. STAHL, La conductibilité électrique de l'air sur l'inlandsis groenlandais, An. Geophys., v. 9, no. 1, pp. 34-43, 1953.

SHERMAN, K. L., Atmospheric electricity at the College-Fairbanks Polar Year Station, Terr. Mag. and Atmos. Elec., v. 42, pp. 371-391, 1937.

SORGE, E., Wiss. Erg. Deutsch. Grönl. Exp. A. Wegener, Brockhaus, Leipzig, v. 3, p. 87, 1939.

THE PHOTO-ELECTRIC COUNTER AND ITS APPLICATION FOR MEASURING DIFFUSION COEFFICIENTS

P. J. Nolan

University College, Dublin, Ireland

Abstract--In the photo-electric nucleus counter, a cloud is formed between a source of light and a photo-electric cell and the concentration of nuclei is estimated from the extinction of the light. Air containing the nuclei under investigation is drawn through a vertical tube 60 cm long and 4 cm in diameter for a sufficiently long time to insure that the air originally present is swept out. The entrance and exit taps are closed and pure air is pumped in through a third tap until a suitable over-pressure is reached. A short time is allowed to elapse so that the air, taking up water from the lining of damp blotting paper, is saturated. The current from the photo-voltaic cell is read by means of a galvanometer. A fourth tap on the tube is opened allowing the air to expand adiabatically. A cloud forms and the galvanometer reading drops quickly to a new value. An intrinsic calibration of the instrument has been carried out by means of a device which enabled the extinctions for any nuclear concentration and for exactly half that concentration to be determined accurately. The absolute values of the nucleus concentration are based on simultaneous determinations with an Aitken counter. The absolute accuracy is of the same order as that of the Aitken counter. The relative accuracy is higher. The development of the photo-electric method of counting has made it possible to employ with much precision a method already in use by which the size of condensation nuclei can be determined. If a stream of air containing particles of any kind is drawn slowly through a tube particles will be lost by diffusion and fall under gravity. In order that the loss by diffusion should be large enough for accurate measurement it was found best to draw the air between parallel surfaces a small distance apart. When the surfaces are vertical the loss by gravity is negligible. By building a pile of plates a number of air streams in parallel are arranged. In this way a sufficiently slow air velocity may be obtained with a conveniently large total air flow. The ratio of the concentrations of nuclei entering and leaving is determined for a measured air flow. From these measurements and the dimensions of the diffusion box the diffusion coefficient of the nuclei can be obtained. The radii of the nuclei may be deduced from the diffusion coefficient by means of the Millikan form of the Stokes-Cunningham Law.

The Aitken nucleus counter, in its original form and in the various modifications, suffers from a number of serious disadvantages. It is difficult to use and to keep in good working order. It deals with a very small sample of air. Successive readings of samples from the same source usually show a wide scatter. The photo-electric counter is easier to use and gives more consistent and more reproducible results.

The photo-electric counter consists of a metal tube 60 cm in length and four cm in diameter. The tube has a lining of damp blotting paper and the axis is held in a vertical position. At the top of the tube there is a lamp house with a small electric lamp at the focus of a convex lens. A parallel beam of light passes through the tube and falls on a photo-voltaic cell at the bottom. The sample of air under test is introduced into the tube. Air which has been purified by passage through a cotton-wool filter, is pumped into the counter until a selected over-pressure, usually 16 cm Hg, is reached. After about half a minute the pressure is released. The sudden expansion cools the moist air, a fog is formed and the minimum reading of a critically damped galvanometer, connected to the photo-cell, is taken. The half-minute delay is to allow the air to become saturated and to lose heat of compression. During this waiting period the galvanometer reading is adjusted to 100 by varying the current through the lamp.

The glass plates closing the ends of the tube are treated with an anti-mist preparation. Immediately above the photo-cell a diaphragm of 2.2 cm aperture is introduced so that the extinction measurements are made on the central core of the fog.

The light intensities at the photo-cell before and after the formation of the fog are denoted I_0 and I. As the intensities are low the response of the photo-cell in linear. Thus the galvanometer readings before and after expansion are proportional to I_0 and I. We can calculate the extinction expressed as a percentage

$$E = 100(I_0 - I)/I_0. \qquad (1)$$

The behavior of the counter when filled with nucleus-free air has been investigated by P. J. Nolan and P. S. MacCormaic. They determined the critical over-pressures for condensation on negative and positive small ions and for the formation of a general cloud. The critical values found were 27, 33, and 40 cm Hg. The corresponding volume expansions deduced from the equation $pv^{1.4}$ = constant are 1.24, 1.29, and 1.35. The corresponding values found by C. T. R. Wilson are 1.25, 1.31, and 1.375. The good agreement of these three critical expansion ratios indicates that the expansion of the counter is truly adiabatic. The critical over-pressure for cloud formation with atmospheric nuclei was found to be between 0.1 and 0.5 cm Hg corresponding to a volume expansion between 0.1 and 0.5 pct.

Calibration--For calibration of the counter a device called a tube bridge, a pneumatic analogue of the Wheatstone bridge, was used. The air current enters at point A and leaves at point C of the bridge ABCD. A sensitive manometer is connected between B and D. Arms BC and DC are long narrow tubes of the same resistance. Arm AD contains a low resistance cotton-wool filter and arm AB contains a rubber tube with a pinch-cock. The bridge is balanced by varying the resistance of arm AB by means of the pinch-cock. Variations in the resistance of the filter with temperature, humidity, or pressure difference may be detected on the manometer. When the bridge is balanced the current of pure air through DC is equal to the current of impure air through BC. The nuclear concentration of the air emerging is exactly one-half the nuclear concentration at entrance.

Nuclei of various origins decaying in a gasometer were used in the calibration experiments. The counter was filled from the gasometer through the tube bridge and an observation of the extinction made. The counter was next filled directly from the gasometer. (To ensure against error due to diffusion loss a second tube bridge without filter was inserted between the gasometer and the counter.) During the decay of the nuclei alternate readings of half and full concentration were made in this way. The values of the extinctions were plotted against the time and curves for full and half concentration were obtained. It is possible to read from the curves the corresponding extinctions at any time during the decay process. Thus a series of pairs of extinctions values may be obtained, each pair corresponding to a certain (so far unknown) concentration of nuclei and to half that concentration. The values of the extinction differences ($E - e = \Delta$) are plotted against E. The shape of the Δ-E curve is of great interest. From E = 5 to E = 25 the graph is nearly a straight line and there is another straight line between E = 25 and E = 50. There are three peaks at E - 56, 72, and 90. From the Δ-E curve an intrinsic calibration curve was plotted. The peaks should give inflexion points on the calibration curve. The peak at 56 is small and the corresponding inflexion is not perceptible. The inflexion corresponding to peak 72 is a well marked feature of the calibration curve. The flat portion at the end of the calibration curve corresponds to the peak at 90.

To complete the calibration the nuclear concentrations corresponding to a number of extinctions values were determined by means of an Aitken pocket counter. The agreement was as good as could be expected in view of the lack of precision of the latter instrument.

Determination of diffusion coefficients--The development of the photo-electric method of counting has made it possible to employ with much precision the Nolan-Guerrini method of determining diffusion coefficients. If a stream of air containing particles of any kind is drawn slowly through a tube, particles will be lost by diffusion and fall under gravity. In order that the loss by diffusion should be large enough for accurate measurement the air is drawn between parallel plates a small distance apart. This has the advantage that when the plates are vertical the loss by gravity is negligible. By building a pile of plates a number of air streams in parallel are arranged. In this way a sufficiently slow air velocity may be obtained with a conveniently large total air flow.

The formula obtained by P. G. Gormley for diffusion in such a thin rectangular tube is

$$n/n_0 = 0.9099e^{-2.8275h} + 0.0531e^{-32.145h} \quad \ldots\ldots\ldots\ldots (2)$$

where n_0 is the particle concentration at the entrance, n is the concentration at the exit, and $h = 4bD\ell/3aQ$. D is the diffusion coefficient; Q is the volume of gas passing per second, 2a = depth, b = breadth, and ℓ = length; a is small compared with b.

In practical application the formula is written

$$Zv/Z = 0.91e^{-x} + 0.053e^{-11.4x} \quad \ldots\ldots\ldots\ldots (3)$$

where $x = 3.77\ b\ell D/aQ$ and the symbol Z is used for nucleus concentration.

A curve is drawn showing the variation of Zv/Z with x (Fig. 1). The ratio of the concentrations

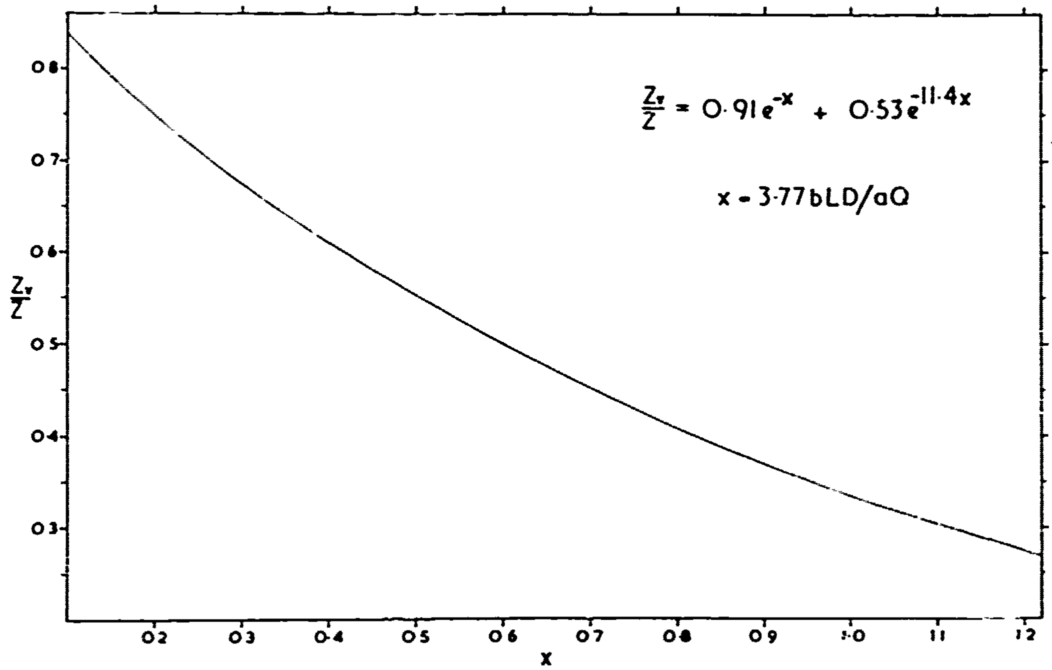


Fig. 1--Variation of Zv/Z with x

entering and leaving is determined for a measured air flow. The value of x corresponding to this ratio is obtained from the graph and thus D is determined.

Numerical example--Length = 60.9 cm, breadth = 9.2 cm, depth = 0.105 cm, number of channels = 11, Q = 1200 cm^3/min.

$$Zv/Z = 0.5 \qquad x = 0.60$$

$$D = 23 \times 10^{-6}\ cm^2 sec^{-1}$$

The radii of the nuclei may be deduced from the diffusion coefficient by means of the Millikan form of the Stokes-Cunningham Law. In Table 1 values of D so calculated are given for a range of values of the radius.

Table 1--Coagulation coefficients

$10^6 r$	$10^6 D$	$10^3 \omega$	$10^9 \gamma$	$10^6 b$	Z/N_0	Z/N_0
cm	cm^2sec^{-1}	$cm^2sec^{-1}volt^{-1}$	cm^3sec^{-1}	cm^3sec^{-1}		single charge
0.5	508	20.3	6.4	0.14	1.06	1.06
1.0	131	5.24	3.3	0.46	1.21	1.21
2.0	34.8	1.39	1.75	1.25	1.59	1.59
3.0	16.5	0.66	1.24	2.1	1.91	1.91
5.0	6.67	0.267	0.84	4.1	2.44	2.31
7.0	3.80	0.152	0.67	6.4	2.85	2.51
10.0	2.17	0.087	0.55	10.4	3.37	2.66
14.0	1.33	0.053	0.47	15.6	4.04	2.76

Coagulation--When nuclei are stored in a large vessel they disappear by coagulation, by diffusion to the walls and by fall under gravity. In favorable conditions it is possible to allow for the last two sources of loss and to study coagulation separately. The loss by coagulation is found to obey the law

$$dZ/dt = -\gamma Z^2 \qquad (4)$$

where γ is called the coagulation coefficient. For spherical particles all of the same size Smoluchowski obtains the result $\gamma = 8\pi rD$.

By means of the photo-electric counter and the diffusion box Nolan and Kennan made determinations of γ and D over a wide range of size using nuclei derived from hot platinum. According to Smoluchowski's theory the value of γ/rD should be about 25. They obtained an average value of 35. The agreement is as close as could be expected especially as the nuclei were undoubtedly heterogeneous. The 8π of the formula must be increased by a factor of from 1.1 to 1.3 to allow for heterogeneity.

In Table 1 the values of the coagulation coefficient are calculated from the formula $\gamma = 8\pi rD$. The mobilities given in the table are for nuclei with one electronic charge and are calculated from the formula

$$\omega/D = \epsilon/kT \qquad (5)$$

ϵ being the electronic charge, k Boltzmann's constant, and T the absolute temperature

This gives $\omega = 40D$ when the mobility is expressed in cm/sec volt/cm and the temperature is 17°C.

Relation between the size of the nuclei and the fraction charged--Simultaneous determinations of the diffusion coefficient and of the ratio Z/N_0, total nuclei to uncharged nuclei, were carried out with stored nuclei derived from platinum. The concentration of uncharged nuclei was determined by passing the air through a condenser to which a field is applied sufficient to remove all charged nuclei. A measurement with the electrodes of the condenser at the same potential gives Z. If equilibrium of ionization has been attained in the vessel

$$\eta_0 N_0 = \eta N \qquad (6)$$

where η_0 is the recombination coefficient of small ions and uncharged nuclei and η is the coefficient for small ions and large ions of opposite sign

$$Z/N_0 = (N_0 + 2N)/N_0 = 1 + 2\,N/N_0 = 1 + 2\,\eta_0/\eta \qquad (7)$$

$\eta > \eta_0$: · that $Z/N_0 < 3$.

If the nuclei are so large that the effect of their electric charge on the collision frequency with small ions is negligible then $\eta = \eta_0$ and $Z/N_0 = 3$, its maximum value.

The equilibrium values found experimentally are given in Table 1 (second last column) and plotted in Figure 2 (dotted line). It may be seen that for large nuclei the values are greater than 3. This is clearly due to the occurrence of multiple charges.

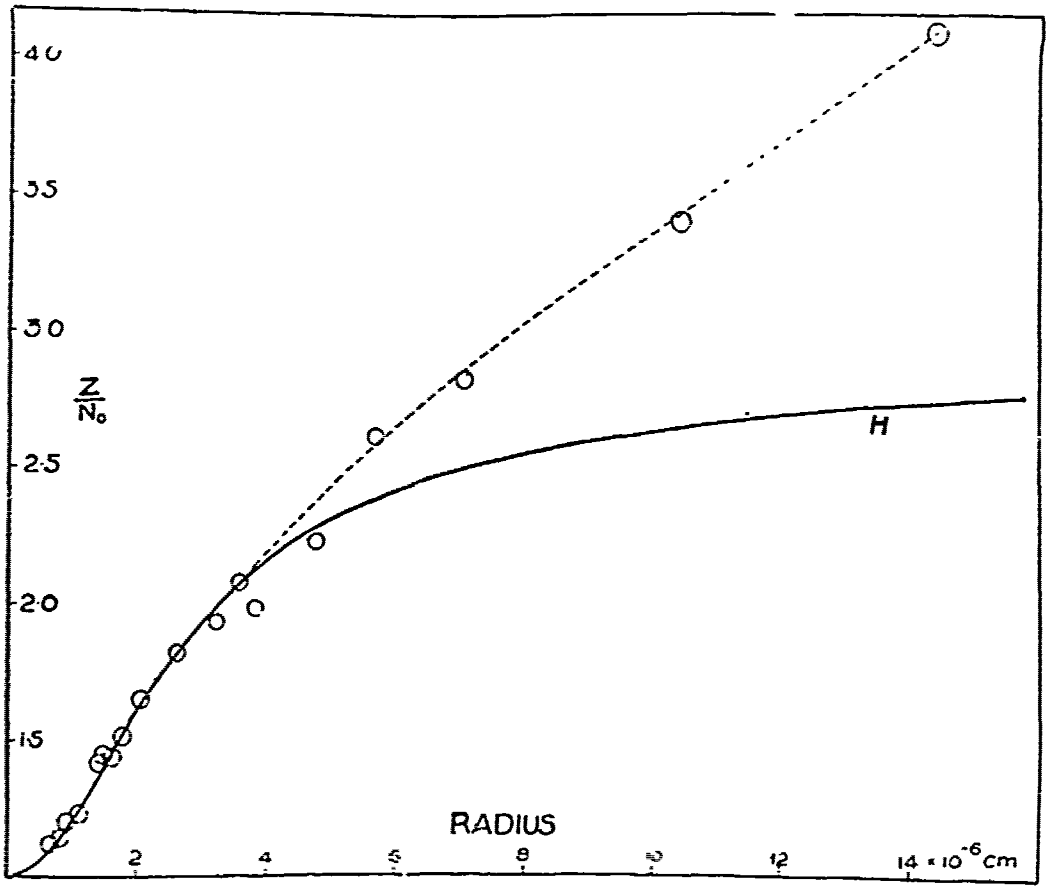


Fig. 2--Relationship of size of nucleus to Z/N_0

By combining two theoretical relations we may deduce values of η_0/η for various radii to compare with those obtained from the experimental values of Z/N_0

Whipple's equation $\quad \eta - \eta_0 = 4\pi\epsilon\omega$ . . . . (8)

Harper's equation $\quad \eta_0 = Hr(1 - e^{-cr})$ . . . . (9)

(small radius $\eta_0 \alpha r^2$, large radius $\eta_0 \alpha r$)

By trial values of the parameters H and c were found which gave the best fit with the experimental values of Z/N_0 for the smaller radii that is for the single-charge region. The agreement with experiment holds up to a radius of 4×10^{-6} cm. The last column of Table 1 gives the theoretical Whipple Harper Z/N_0 so found and it is marked 'single charge.' These numbers are plotted

in Figure 2, curve H.

In Table 1 the third last column gives values of the quantity b of the equation $q = \alpha n^2 + bnZ$. The values are calculated by an extension of the previous theory on the assumption that the multiply-charged nuclei are all doubly charged.

The application of considerations of thermodynamic equilibrium to the system of small ions and nuclei produces results which agree closely with experiment. So although the justification of this application seems doubtful it is of interest to quote the results.

From the Boltzmann Distribution Law we deduce

$$N_1/N_o = N_2/N_o = e^{-p^2\epsilon^2/2rkT} \quad \text{.................... (10)}$$

where ϵ is the electronic charge, p is the number of unit charges and $p^2\epsilon^2/2r$ is the electric energy of the nucleus considered as a sphere of radius r, N, the concentration of positively charged nuclei, and N_2 the concentration of negatively charged nuclei.

The results of the application of this formula are shown in Table 2 in the columns marked Boltzmann, one giving values of Z/N_o in which only single charges are included. Another column gives values deduced from the Whipple-Harper formula with parameters adjusted to obtain agreement with the Boltzmann figures. It may be seen that the agreement is good except for the smaller radii.

Table 2--Values of Z/N_o

$10^6 r$	Multiple charges			Single charge		
	Bricard	Experiment (Nolan and Kennan)	Boltzmann	Boltzmann	Whipple-Harper	Bricard
cm						
0.5	...	1.06	1.006	1.006	1.045	...
1.0	1.49	1.21	1.11	1.11	1.16	1.49
2.0	1.88	1.59	1.48	1.47	1.46	1.81
3.0	2.13	1.91	1.81	1.77	1.74	2.00
5.0	2.66	2.44	2.34	2.12	2.12	2.30
7.0	3.03	2.85	2.76	2.33	2.34	2.46
10.0	3.50	3.37	3.30	2.50	2.52	2.55
14.0	3.92	4.04	3.91	2.63	2.64	2.63

When multiple charges are included we obtain very good agreement with the experimental results. It may be noted that nuclei with p = 2 appear at radius 2×10^{-6}, p = 3 at r = 4×10^{-6}, p = 4 at r = 7×10^{-6} and p = 5 at 12×10^{-6}. We have added Bricard's theoretical figures for multiple charges and for single charge.

Atmospheric nuclei--In making observations on the nuclei in the free atmosphere difficulties arise because of rapid fluctuations in the quantities measured. These difficulties may be overcome by using two photo-electric counters through which equal air-streams are drawn in parallel. The diffusion coefficient may be found by placing the diffusion apparatus in one branch. Simultaneous values of Z and of Z_v are thus obtained. Similarly by using two condensers in parallel, one with field and the other without, simultaneous values of Z and N_o may be obtained.

The values found for the radii of the nuclei vary between 1×10^{-6} and 6×10^{-6} cm but the bulk of them lie between 2×10^{-6} cm and 3.5×10^{-6} cm. A high degree of correlation has been found between the size of the nuclei and the humidity of the atmosphere.

Absence of equilibrium--Simultaneous measurements of Z/N_o and of the radius show that in general the condition is not one of equilibrium. There is a wide scatter in the values of Z/N_o for

any one size. The equilibrium values given in Table 1 and shown in Figure 2 appear only as the higher limit, the bulk of the values of Z/N_0 being much lower. This suggests that the nuclei are mainly uncharged at the moment of production. Between production and measurement there is not sufficient time for them to come into equilibrium with the small ions. If all the nuclei are originally uncharged in a region where there is a constant concentration n of small ions the half-value period for equilibrium is approximately $0.7/(2\eta_0 + \eta)n$. In Dublin this is of the order 10 to 15 minutes.

From the foregoing we see that ionization balance equations cannot apply strictly to any region where there exists a large fraction of fresh uncharged nuclei. It is possible to explain in this way the low values for q obtained for Kew (Scrase) and Washington (Wait) from measurements of N, N_0, and the positive and negative conductivities. Errors arising from the application of equilibrium formulas of the type $q = \alpha n^2 + bnZ$ in which Z and not N are used, are much smaller. Since $b = \eta_0 + (\eta - 2\eta_0)N/Z$, b is independent of N if $\eta = 2\eta_0$. For values of the radius greater than 2×10^{-6} cm the change in b produced by a considerable departure from equilibrium will not be very serious. The Schweidler law may therefore be expected to hold approximately for large nuclei whether there is equilibrium or not.

When atmospheric nuclei are stored and observations of Z/N_0 and the radius are made during a few hours after enclosure it is found that Z/N_0 and the radius increase. Initially Z/N_0 increases rapidly while the radius increases very slowly. The value of Z/N_0 reaches the equilibrium value pertaining to its size in about one hour. Afterwards the variation with radius corresponds approximately with the equilibrium curve of Figure 2.

Approach to the equilibrium charge distribution from the opposite direction is shown by the nuclei produced by bubbling air through water. Immediately after production the average charge per ion is 23 electronic charges and Z/N_0 varies, with bubbling pressure, from 20 to 9. When these nuclei are stored Z/N_0 is found to decrease rapidly without any significant increase in radius until the equilibrium value is approximately reached. Then the variation of Z/N_0 with radius corresponds roughly with the equilibrium curve.

It is interesting to note that in both cases the value of Z/N_0 slightly over-shoots the equilibrium value.

References

BRICARD, J., L'equilibre ionique de la basse Atmosphere, J. Geophys. Res., v. 54, pp. 39-52, 1949.

HARPER, W. R., On the theory of combination coefficients for large ions and uncharged particles at any pressure, Phil. Mag., v. 18, pp. 97-113, 1934; also v. 20, p. 740, 1935.

NOLAN, J. J., and V. H. GUERRINI, The diffusion coefficients and velocities of fall in air of atmospheric condensation nuclei, Proc. R. Irish Acad., v. 43, pp. 5-24, 1935.

NOLAN, J. J., P. J. NOLAN, and P. G. GORMLEY, Diffusion and fall of atmospheric condensation nuclei, Proc. R. Irish Acad., v. 45, pp. 47-63, 1938.

NOLAN, P. J., and L. W. POLLAK, The calibration of a photo-electric nucleus counter, Proc. R. Irish Acad., v. 51, pp. 9-31, 1946.

NOLAN, P. J., and E. L. KENNAN, Condensation nuclei from hot platinum; size, coagulation coefficient and charge-distribution, Proc. R. Irish Acad., v. 52, pp. 171-190, 1949.

NOLAN, P. J., and D. J. DOHERTY, Size and charge distribution of atmospheric condensation nuclei, Proc. R. Irish Acad., v. 53, pp. 163-179, 1950.

NOLAN, P. J., and P. G. TEDDE, Condensation nuclei and meteorological elements in Dublin, Arch. Met. Geophys. und Biokl., v. 3, no. 4, pp. 374-385, 1950.

NOLAN, P. J., and P. S. MacCORMAIC, Geophysical Bulletin 7, School of Cosmic Physics, Dublin Inst. for Advanced Studies, 1953.

WHIPPLE, F. J. W., Relations between the combination coefficients of atmospheric ions, Proc. Phys. Soc., v. 45, pp. 367-380, 1933.

EFFECTS OF WIND AND SPACE CHARGE ON CORONA POINT DISCHARGE, PARTICULARLY FROM AIRCRAFT[a]

Seville Chapman

Cornell Aeronautical Laboratory, Inc.
Buffalo 21, New York

Abstract--In a system for maintaining zero electrostatic charge on aircraft, where electric-field meters on the surfaces of the wings control a high-voltage corona discharge point behind the tail of the aircraft, the primary factors influencing the magnitude of blow-away discharge current i are point potential V, aircraft speed v, point geometry, and space charge from the already discharged current. V must be large enough to create an electric field vector toward the rear to drive the discharge current into the space charge behind the point, but since this same V creates a field vector forward toward the aircraft skin, the point must be disposed so that the wind past the point prevents return current to the aircraft. The problem is approached mathematically from several points of view, to evaluate constants F, G, and H in $i = \epsilon_0 (FkV^2/\ell + GvV + H\ell v^2/k)$, where k is the mobility and ℓ a length. The current should vary with the first powers of the speed and point potential, and be independent of mobility, and hence of polarity and altitude. For an aircraft speed of 100 m/sec and a point potential of 100 kilovolts, the author considers that current should lie in the range 200-250 microamperes although calculations based on different approximations vary from 175-395 microamperes. Experiments in the laboratory with wind simulated by an electric field yield 225 microamperes. Meager and doubtful in-flight data imply current of about 200 microamperes.

Introduction--Reasons for maintaining zero electrostatic charge on aircraft include alleviating effects of precipitation static [GUNN and Others, 1946], avoiding explosions during refueling operations in flight, or avoiding distortions of electrostatic conditions while in-flight measurements are being made of such quantities as the electrical conductivity of the air. For example, when aircraft fly through precipitation, they frequently become charged electrostatically at a rate of 100 microamperes or more. Since the capacitance of an aircraft such as a B-29 is approximately 1000 picafarads (1 picafarad or 'puff' = 1 micromicrofarad = 10^{-12} farad), it is clear that the rate of change of potential may be 10^5 volts/second. After a few seconds many undesirable phenomena occur, especially those which interfere with electrostatic measurements or with communications.

The basis for this discussion is an instrumentation system [PELTON and Others, 1953] (discussed in the next section) which senses the electrostatic charge on the aircraft and uses this information to control a high-voltage corona discharge point behind the tail of the aircraft, so that excess charge may be discharged by the corona point and blown away by the slip-stream.

While corona points have been used to discharge aircraft as just described, and for investigating atmospheric electricity from ground stations [CHALMERS, 1949, 1954] most calibrations have been done in still air in the laboratory. In flight, and generally at a ground station, there is wind past the corona point. Since conditions with wind are quite different from those without, the effects of wind receive primary attention in this discussion. We shall see that the usual type of calibration done in still air is completely inapplicable to the case of an isolated point in wind.

The zero electrostatic charge on aircraft (ZECA) instrumentation system--The electrostatic charge on the aircraft may be determined by measuring the surface electrostatic field with generating field meters (sometimes called generating voltmeters or field mills). Almost invariably there is an electrostatic field in the atmosphere; hence the electric field at the surface of the aircraft consists of two components, that due to the ambient field (which is vertical in fair weather), and

[a]This article is a revised and somewhat extended version of a paper of the same title presented at the Conference. A more complete discussion than is given here, including all mathematical derivations, may be found in the author's Cornell Aeronautical Laboratory Report No. 66.

that due to self-charge. Clearly a minimum of two meters is required to distinguish between these two fields. There are several sets of two points on the aircraft where two meters could be placed so that their readings could be combined to yield self-charge. Most of these points, however, are in awkward positions, such as where the fuselage is highly curved, and where slight inaccuracies of positioning the meters would give false indications.

The ambient electric field may have horizontal components as well as vertical components. All components may be determined in addition to the self-charge of the aircraft. A convenient arrangement is to place two meters far out on each wing well away from the fuselage and engines, but not close to the wing tips. In these regions the wings are fairly flat, and one may calculate the 'form factors' associated with any given location. Meters should be placed along the electrical center lines of the wing so as to be insensitive to longitudinal horizontal fields (see Fig. 1).

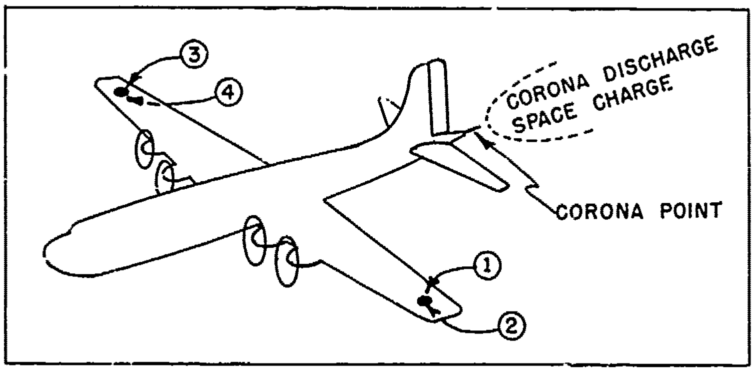


Fig. 1--Location of field meters and corona point in the ZECA system

When due account is taken of the form factors it is not difficult to see that

$$E_1 - E_2 + E_3 - E_4 \propto E_z \quad (1)$$

$$E_1 + E_2 - E_3 - E_4 \propto E_y \quad (2)$$

$$E_1 + E_2 + E_3 + E_4 \propto E_Q \quad (3)$$

where E_1, E_2, E_3, and E_4 are the form-factor corrected readings of meters 1, 2, 3, 4; E_z is the vertical component of the ambient electric field, E_y is the transverse horizontal component, and E_Q is the field at the meters due to electrostatic charge on the aircraft. Actually there is some redundancy since four meters are used to give three quantities. In fact, if one of the meters becomes inoperative in flight, it is possible to switch the meters so that only three are needed. For convenience, however, and from symmetry, it seems best to install four meters as shown. If the longitudinal component of the ambient field is required also, then a fifth meter should be installed, presumably directly on the front of the nose.

The readings of the several meters are combined to control a 100-kilovolt dc voltage supply. One side of the voltage supply is connected to the airframe, while the other is connected to a corona point insulated from the skin of the aircraft. The tip of the corona point is about 40 cm behind the tail of the aircraft, where in principle it is subjected to the full force of the slip-stream past the aircraft.

Obviously it is important to estimate the magnitude of corona current which can be obtained, in terms of the potential applied to the point, the aircraft speed, ion mobility, and geometrical quantities such as the distance of the point (or points) behind the aircraft. Such an expression is required so that design information can be obtained, performance data can be estimated, and results

can be analyzed properly. Assertions have been made that current blown away from the airplane by unipolar ions created in a gaseous discharge will be limited to rather small values of discharge current of about 15 microamperes. While we have measured currents greater than this, in order to understand the mechanism of discharge of the aircraft (as distinct from the detailed mechanism of corona discharge itself [LOEB, 1948]), it seems worthwhile to endeavor to calculate the currents which may be obtained. For the sake of comparison, results are normalized to conditions with a point potential of 100,000 volts and with an aircraft flying with a speed of 100 m/sec at an altitude of about 18,000 ft, where the pressure is half of sea-level pressure.

Basic mathematical relations--The fundamental relations governing the motion of space charge created by the corona point are

$$\nabla^2 V = -\rho/\epsilon_0 \quad (4)$$

$$E = -\operatorname{grad} V \quad (5)$$

$$u = kE + v \quad (6)$$

$$\operatorname{div}(\rho u) = 0 \text{ except at the point and at electrodes} \quad (7)$$

$$i = \rho u S \quad (8)$$

where

V = the electric potential

ρ = the volume space charge density

ϵ_0 = the permissivity of empty space = 8.854×10^{-12} farad/m

E = the electric field

u = the ion speed

k = the ion mobility ($+1.6 \times 10^{-4}$ or -2.2×10^{-4} m^2/sec volt at sea-level or about 4×10^{-4} m^2/sec volt at 18,000 ft altitude)

v = the airspeed of the airplane

i = the current

S = an appropriate area

Eq. (4) and (5) are the fundamental equations of electrostatics, (6) essentially defines mobility (since in still air, ion speed = kE), (7) is the equation of continuity, and (8) relates current to space charge density.

Other useful equations can be derived from (4)-(8). Complete derivations are given elsewhere [CHAPMAN, 1955] and the results only are given below.

Sometimes it is convenient to consider the effect of wind blowing ions along as equivalent to an electric field E_w. From (6), E_w is seen to be

$$E_w = v/k \quad (9)$$

In the absence of space charge, at a distance r from a point charge q, the electrostatic equations can be written

$$E = -q/4\pi\,\epsilon_o r^2 \quad (10)$$

$$E = -V/r \quad (11)$$

from which it is readily seen that $V = q/4\pi\,\epsilon_o r$.

Consider a spherical system without wind having a small grounded inner electrode and an outer electrode at a fixed potential, with total space charge current i between electrodes. At any point at radius r within the system or at the outer electrode, to a very close approximation

$$i = 6\pi\,\epsilon_o\,k\,r\,E^2 \quad (12)$$

$$i = (3\pi\,\epsilon_o/2)\,kV^2/r \quad (13)$$

$$E = -V/2r \quad (14)$$

Consider a semi-infinite cylinder of space charge of uniform density ρ, whose radius is r_3, and whose axis lies along the X-axis. The cylinder extends to infinity from a plane normal to the X-axis at x_o. It may be imagined that the space charge was emitted at a rate $i = d\rho/dt$ by a source of area πr_3^2 traveling with a speed $\bar{v}$ along the axis. The space charge is considered to remain fixed and not to spread out radially. It is apparent that the

$$\text{linear charge density} = i/v = \pi r_3^2 \rho \quad (15)$$

The electric field E_c at the origin of coordinates is directed along the axis, its value is

$$E_c = (i/2\pi\,\epsilon_o r_3 v)\left[\sqrt{1 + (x_o/r_3)^2} - x_o/r_3\right] \quad (16)$$

If the end of the cylinder is at the origin, then $x_o = 0$ and for the field E_{co} (16) simplifies to

$$E_{co} = i/2\pi\,\epsilon_o r_3 v \quad (17)$$

From (16) and (17) we see that most of the field at the end of the cylinder is due to space charge close to the end. Space charge between the end and $x = 0.75r_3$ contributes half of the field, while space charge beyond $x = 5r_3$ contributes only one-tenth of the field.

Consider a paraboloid of space charge whose axis lies along the X-axis. The paraboloid has a radius R_o at the origin and extends to infinity along the positive direction of the axis. Because of the self-repulsive nature of space charge, it can be shown [CHAPMAN, 1955] that the space charge will spread out in the form of a paraboloid whose radius R at an abscissa x is given by

$$R^2 = R_o^2 + (ki/\pi\,\epsilon_o v^2)\,x \quad (18)$$

where

i = current or rate of emission of space charge

v = speed of source

k = mobility of the ions comprising the space charge

If the paraboloid is truncated at an abscissa x and extends to infinity beyond x, then the electric field at the origin is given by

$$E_p = (v/2k)\ \ln \frac{(\sqrt{R_o^2 + bx + x^2} + x + b/2)\,(b^2 - 4R_o^2)}{2\,(R_o^2\, b + b^2 x - 2R_o^2\, x - 2R_o^2 \sqrt{R_o^2 + bx + x^2})} \quad \ldots\ldots (19)$$

where

$$b = ki/\pi\, \epsilon_o v^2 \quad \ldots\ldots (20)$$

If the paraboloid is truncated at the origin x = 0 where the radius of truncation is R_o, the field at the origin E_{po} becomes

$$E_{po} = (v/k)\ \ln\,[1 + (ki/2\pi\, \epsilon_o v^2 R_o)] \quad \ldots\ldots (21)$$

To find the field on the X-axis at a point $x = -2r_2$ of the paraboloid truncated at the origin (18), it is convenient to translate the truncated paraboloid of (18) by a distance $2r_2$, so that it is now truncated at $x = 2r_2$. Then we can find the field E_p at a distance $2r_2$ from a truncated paraboloid whose radius of truncation is R_o, this field being formed by a current source i having a speed v. We find from (18) and (19) that

$$E_p = (v/2k)\ \ln \frac{([\sqrt{R_o^2 + 4r_2^2} + 2r_2] + b/2)\,(b^2/4 - [R_o^2 - 2br_2])}{(R_o^2\, b/2 - [R_o^2 - 2br_2]\,[\sqrt{R_o^2 + 4r_2^2} + 2r_2])} \quad \ldots\ldots (22)$$

where b is given by (20).

Dimensional analysis--We can learn some facts about corona discharge from dimensional analysis. In electrical phenomena we may choose four fundamental quantities, for example, length, mass, time, and charge. Actually it is simpler to take charge, potential, length, and time. By the usual type of analysis the relevant parameters can be combined to yield the following result for the blow-away current i

$$i = \epsilon_o\,(FkV_1^2/\ell + GvV_1 + H\,\ell\, v^2/k) \quad \ldots\ldots (23)$$

where

ϵ_o = the permissivity of empty space = 8.854×10^{-12} farads/m

F, G, H, are non-dimensional coefficients undetermined by the dimensional analysis

k = the mobility of the ions

V_1 = the potential of the discharge point relative to the aircraft skin

ℓ = some geometrical length or combination of lengths

v = aircraft speed

Three special cases are of interest.

First, suppose the point is at rest in the air (v = 0) as in a laboratory test. Two of the terms vanish, and the corona current is proportional to V_1^2, and also to k. Since the ratio of positive to negative mobilities is 1.6/2.2, the current at a given potential would be expected to vary in the same ratio as polarity is changed. Further, mobility varies inversely with density. The isothermal density of the atmosphere decreases exponentially with altitude, the density at 18,000 ft being about half that at sea-level, and the density at 36,000 ft being about one-quarter that at sea-level.

Therefore, one would expect current to vary accordingly in altitude chamber tests. All of these effects are observed quite rigorously [for example, PELTON, 1953, Fig. 9].

Second, suppose that no potential is applied to the discharger. Again two terms vanish in (23). This is virtually the case in the Philco system [GREEN and LAURENT, 1950], where the outer cylinder is at the same potential as the airplane skin, and the high voltage points are shielded by the surrounding cylinders. Although their wind tunnel tests were hardly definitive, the current did vary with a power of the wind speed. Theoretically one would expect the current to vary with the square of the wind speed.

Third, suppose that there is no significant geometrical distance in the experiment. This would be the case if the corona point were isolated far enough behind the aircraft to prevent return current from flowing back to the aircraft skin. Once again two terms in (23) vanish, and now the current is proportional to the aircraft velocity and to the point potential. Further, the current will be independent of mobility, and hence independent of polarity (although k+ is not equal to k-), as well as independent of altitude (although k varies with altitude). In wind, an independence of polarity and a linear dependence on potential has been reported [LANGMUIR, 1945].

Any theory of the magnitude of corona discharge current must reduce dimensionally to these cases.

Physical relations--When an aircraft becomes highly charged in flight, it is because an excess of current of one polarity is being delivered to it, generally by impact of 'frictional' electrification all over its frontal area. Most regions in the atmosphere are electrically neutral, or at least neutral in comparison with considerations involving currents of many microamperes; hence the airplane will acquire one sign of charge while it leaves behind it a broad region of space charge of opposite polarity. If the electrostatic charge on the aircraft is maintained at zero by an active corona point in the tail of the aircraft, as in the ZECA system noted above, then there will be a narrow dense region of space charge discharged by the corona point directly behind the point. Subsequently, this narrow dense region of space charge is assumed to have different mathematical forms, such as a cylinder, or paraboloid.

At large distances behind the aircraft, the two space charges of opposite polarity will intermingle and exert no influence on the discharge. Close to the point, however, the broad space charge will have a minor influence, so that we shall be concerned mainly with the narrow dense region of space charge just behind the point.

Clearly, very close to the isolated corona point, there must be spherical symmetry (or almost spherical symmetry), since virtually all of the effects will be associated with the point potential and wind will be unimportant. It has already been mentioned (see Eq. (18)) that far behind the point the space charge will assume the form of a paraboloid. We thus have boundary conditions defined in general terms. It is the purpose of the mathematical discussions which follow to try to fit a solution to these conditions.

As a method of procedure we may assume that out to a certain distance from the point, spherical conditions apply; beyond that distance the situation may be described in terms of a cylinder or truncated paraboloid of space charge (see Fig. 2). Point potential V_1, ion mobility k, aircraft speed v may be assumed to be known. There are four main unknown parameters: discharge current i, radius r_2 of the sphere about the corona point in which spherical conditions apply, radius r_3 of the cylinder or the radius R_0 of truncation of the paraboloid (depending on which model is adopted for calculation), and the potential V_2 of the sphere of radius r_2. To solve for these four unknowns we must have four physical conditions for which we can write appropriate relations. Physical reasoning suggests the following conditions as being applicable (although there are others that may be chosen [CHAPMAN, 1955]:

Condition I--Directly behind the point the electric field vector toward the rear associated with the point potential must balance the electric field vector forward associated with the narrow dense

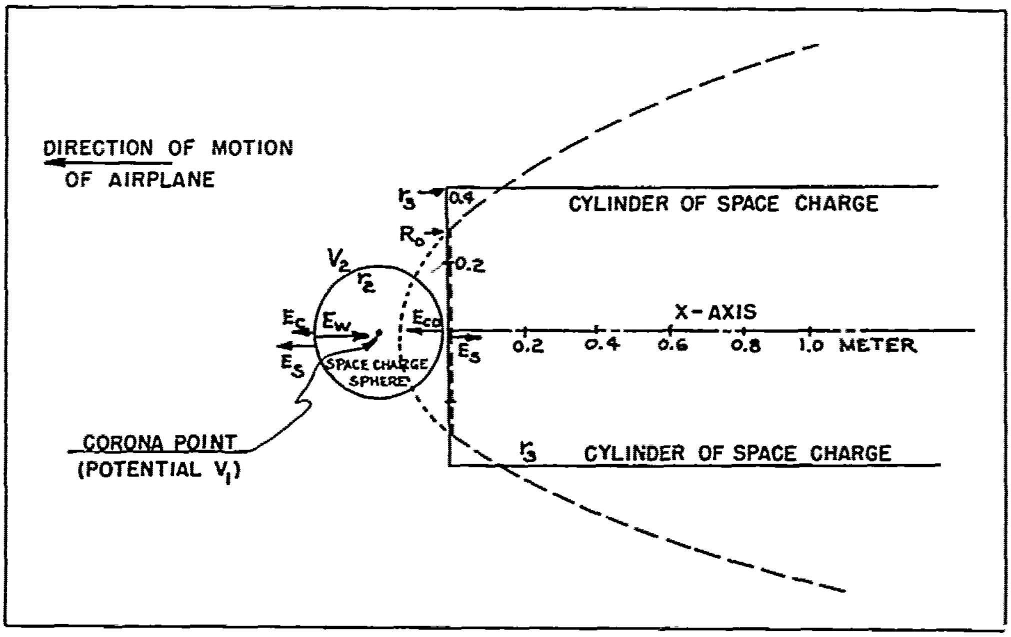


Fig. 2--Geometry of the methods of the space-charge sphere and cylinder (solid line) or truncated paraboloid (broken line)

region of already-discharged space charge. In other words, the point potential must be great enough to force the ions into the opposing already-discharged space charge.

Condition II--Forward of the point toward the aircraft skin, the sum of the electric field vectors associated with the point potential and with the narrow dense region of already-discharged space charge must be balanced by the effective field vector of the wind. In other words, the point potential tends to create an electric field that drives ions back to the airframe; hence there must be a strong enough wind past the point to blow the ions away from the airplane and thus prevent return current to the aircraft. If discharge current returns to the aircraft, it does not influence the net charge on the airplane, and therefore serves no function.

Condition III--In the space charge sphere where electrical forces predominate over wind forces, (13) must apply. We understand by V the potential difference between the point and the surface of the sphere, that is, $V_1 - V_2$.

Condition IV--Some criterion must be applied to relate the point potential and the potential of the surface of the sphere. Subsequently the relation $V_2 = V_1/3$ is derived; and a different relation is suggested.

From these four conditions, in principle we can solve for all the unknowns of interest. The validity of the solution depends, of course, upon the validity of the conditions. In the subsequent paragraphs four different approaches are used to apply the conditions.

The V/3 rule; $V_2 = V_1/3$--Consider a spherical region of radius r_2 around the corona point. Within this region assume that electrical and space charge forces on the ions predominate over the force due to the wind (see Eq. (9)), so that the wind is assumed not to exist. Within the sphere, (12), (13), and (14) apply. Outside of the sphere, suppose that the wind force predominates over the space charge forces, so that we may assume that the free space equations, (10) and (11), apply. (This last assumption neglects the effect of the narrow dense region of space charge behind the point, but we shall take this into account in the later section on method of variation.)

The potential of the corona point relative to infinity (or relative to the aircraft skin, providing the aircraft is zero-charged) is V_1. The potential on the surface of the space charge sphere is V_2.

Just within the surface of the space charge sphere, from (14) the radial electric field is

$$E_{in} = -(V_1 - V_2)/2r_2 \quad (24)$$

Just outside the surface of the space charge sphere, from (11) the radial electric field is

$$E_{out} = -V_2/r_2 \quad (25)$$

Since there is no finite space charge on the boundary, $E_{out} = E_{in}$ and hence

$$V_1 - V_2 = 2V_2 \quad (26)$$

or

$$V_2 = V_1/3 \quad (27)$$

Thus, if a point at infinity is considered to have zero potential, the potential on the surface of the space charge sphere is one-third the potential of the point. Eq. (27) will be referred to as Condition IV.

The conclusion of (27) may be reached also by a more elegant argument [LANGMUIR, 1945].

Method of the simple space charge sphere--The following analysis is a simple one, and is not rigorous since it neglects the inhibiting influence of the electric field of the already-discharged space charge. It is included because most of the material in this section is required for the two following sections, which are more rigorous, and do consider the influence of the already-discharged space-charge.

As above, let us suppose [LANGMUIR, 1945] that all of space may be divided into two regions. The inner region about the corona point of potential V_1 is a sphere of radius r_2 having a surface potential V_2. Within this region space charge (12), (13), and (14) apply. The outer region comprises all the rest of space. In the outer region space charge forces may be neglected and only wind forces (Eq. (9)) apply. In this situation we have seen that Condition IV is

$$V_2 = V_1/3 \quad (28)$$

In (13), the potential difference between the corona point and the sphere is $V_1 - V_2$; thus Condition III is

$$i = (3\pi\epsilon_0/2)[k(V_1 - V_2)^2/r_2] \quad (29)$$

If we substitute (28) we obtain

$$i = 2\pi\epsilon_0 k V_1^2/3r_2 \quad (30)$$

Since we consider that space charge effects may be ignored outside the sphere of radius r_2, from (11) and (28) for the radial electric field E_s just outside the surface of the sphere we have

$$E_s = V_1/3r_2 \quad (31)$$

Now let us apply a variant of Condition II, and take the field at the surface of the sphere E_s to be just equal to the wind field $E_w = v/k$ (Eq. (9)). Thus

$$V_1/3r_2 = v/k \quad (32)$$

When (29) and (30) are combined we have the results

$$i = 2\pi \epsilon_o v V_1 \quad \text{(33)}$$

$$r_2 = kV_1/3v \quad \text{(34)}$$

If we substitute our normalized values $v = 100$ m/sec, $V_1 = 100{,}000$ volts, and $k = 4 \times 10^{-4} m^2$/sec volt,

$$i = 555 \times 10^{-6} \text{ amperes or } 5[illegible] \text{ microamperes} \quad \text{(35)}$$

$$r_2 = 0.133 \text{ meter} \quad \text{(36)}$$

It is to be noticed that the blow-away current is proportional to the first power of the speed and the first power of the point potential. The current is independent of mobility and any distances. Eq. (33) is consistent with the dimensional analysis of (23).

<u>Method of the space-charge sphere and cylinder</u>--Here we consider that there is a space charge sphere about the corona point in which wind forces are neglected, and behind this sphere there is a non-expanding cylinder of radius r_3 of already-discharged space charge, as shown in Figure 2. We make use of Conditions III and IV as in the previous section so that (30) and (31) are applicable here too.

Condition I specifies that the axial field E_{co} at the end of the cylinder of already-discharged space charge, given by (17) is equal to the radial field E_s at the surface of the space charge sphere given by (31).

Thus

$$E_s = E_{co} \quad \text{(37)}$$

or

$$V_1/3r_2 = i/2\pi \epsilon_o r_3 v \quad \text{(38)}$$

Condition II specifies that $E_c + E_s = E_w$, where

- E_c is the field at the forward surface of the sphere, from the cylinder of already-discharged space charge, and is given by (17)
- E_s is the field at the surface of the space charge sphere given by (31), and
- E_w is the wind field given by (9)

Thus

$$E_w = E_s + E_c \quad \text{(39)}$$

or

$$v/k = V_1/3r_2 + (i/2\pi \epsilon_o r_3 v)\left[\sqrt{1 + (2r_2/r_3)^2} - 2r_2/r_3\right] \quad \text{(40)}$$

The solution of (30), (38), and (40) is [CHAPMAN, 1955]

$$r_3 = kV_1/v \quad \text{(41)}$$

$$r_2 = 10kV_1/21v \quad (42)$$

$$i = 1.40\pi\, \epsilon_o v V_1 \quad (43)$$

and of course

$$V_2 = V_1/3 \quad (44)$$

Substituting normalized values $v = 100$ m/sec, $V_1 = 10^5$ volts, and $k = 4 \times 10^{-4} m^2$/sec volt, we have

cylinder radius	$r_3 = 0.40$ meter	(45)
sphere radius	$r_2 = 0.191$ meter	(46)
current	$i = 388 \times 10^{-6}$ amperes	(47)
sphere potential	$V_2 = 33{,}000$ volts	(48)

The form of (43) is the same as for (33), the only difference being the numerical coefficient. Eq. (41, (42), (43), and (27) are the solution for the four unknown parameters previously cited, as determined by the four conditions, applied to the non-expanding cylinder of space charge for the narrow dense region of space charge behind the corona point.

Method of the space charge sphere and paraboloid--If we replace the non-expanding cylinder of space charge by the truncated paraboloid referred to by (19), (20), and (21), and shown in Figure 2, then in the analysis just presented we should replace E_{co} by E_{po} and E_c by E_p. The algebra is extremely tedious and solutions must be obtained in part by trial and error. The results are [CHAPMAN, 1955]

radius of truncated paraboloid	$R_o = 0.274$ meter	(49)
radius of space charge sphere	$r_2 = 0.188$ meter	(50)
current	$i = 394 \times 10^{-6}$ amperes	(51)
sphere potential	$V_2 = 33{,}000$ volts	(52)

It is seen that the results here are not very different from those in the immediately preceding case.

The method of variation of f; $V_2 = fV_1$--The method of the sphere and cylinder may be repeated without, however, using the result of V/3 rule, that is, that the sphere potential V_2 is $V_1/3$, where V_1 is the point potential. Instead we may place

$$V_2 = fV_1 \quad (53)$$

where the fraction f is a parameter whose value, as we shall see, lies somewhere in the range from about 0.3 to 0.5. Results for a few arbitrary values of f are given in Table 1.

The problem now is to determine a physical basis for selecting the proper value of f. The results for the space charge sphere and cylinder constitute the first line of figures. In that discussion, above, the presence of the narrow dense region of space charge behind the space charge sphere was ignored. While we must not be too rigid in our thinking regarding the physical existence of a mathematically defined space charge sphere, it does seem true that the presence of the narrow dense region of space charge so near to the sphere ought to give it a surface potential greater than would be the case if the narrow dense region of space charge were not there.

Table 1--Results for various values of the parameter f

Parameter f	Current i	Sphere r_2	Cylinder r_3	Field E_s	Wind field $E_w = v/k$
	μ amp	m	m	v/m	v/m
0.333	388	0.191	0.40	175,000	250,000
0.40	292	0.205	0.27	195,000	250,000
0.442	245	0.212	0.212	199,000	250,000
0.48	197	0.228	0.169	210,000	250,000
0.50	179	0.231	0.150	215,000	250,000

The capacitance of an isolated object is defined as the ratio of its charge to its potential. It is well known that if C is the capacitance of an isolated conducting sphere, then the capacitance of two equal touching conducting spheres is 2C ln 2, or 69.3 pct of the sum of the capacitances of two isolated spheres. Thus with a given charge on a sphere, its potential is increased in the ratio 1/0.693 by the presence of a second equally charged sphere.

We may consider the second sphere as an approximation to the narrow dense region of space charge behind the space charge sphere. Applying this argument, we might expect the V/3 rule to be modified to $V/(3 \times 0.693)$, or in (53) we might expect

$$f = 0.333/0.693 = 0.480 \quad (54)$$

Hence the fourth line of figures in Table 1 would be the correct one; that is, the current would be 197 microamperes.

Alternatively we might select a value of f intermediate between 0.333 and 0.480. Since ions do move away from the sphere about the point, there is the presumption that the second sphere should be chosen to have a smaller potential than the first, an effect that would yield a value for f of less than 0.48. The solution for f = 0.48 is somewhat disturbing also, since r_3 is less than r_2, and such a geometry does not seem particularly appropriate. Again we might select the condition $r_2 = r_3$ or f = 0.442. In any case 0.333 seems too small for f, and probably the value lies between 0.4 and 0.5.

The mathematical argument is not continued beyond this point in this paper, although further ideas are given elsewhere [CHAPMAN, 1955].

Still air simulation--Consider a laboratory set-up in still air, the set-up consisting of two horizontal parallel plates separated a distance d, as shown in Figure 3. A potential V is applied to the upper plate, and a corona point is placed through a hole in the lower plate so that the point is at a height h above the lower plate. At the same height h, but at a place removed from the point, the potential in the space between the planes is V_{ps}, so that the potential difference between this region and the point is V_{ps}.

Since the electric field between the plates is V/d, ions of mobility k will move in the region between the plates at a speed kV/d. Thus the arrangement of Figure 3 simulates a condition where ions are in a simulated wind of speed

$$v_s = kV/d \quad (55)$$

and the point is at a potential

$$V_{ps} = Vh/d \quad (56)$$

relative to its surroundings.

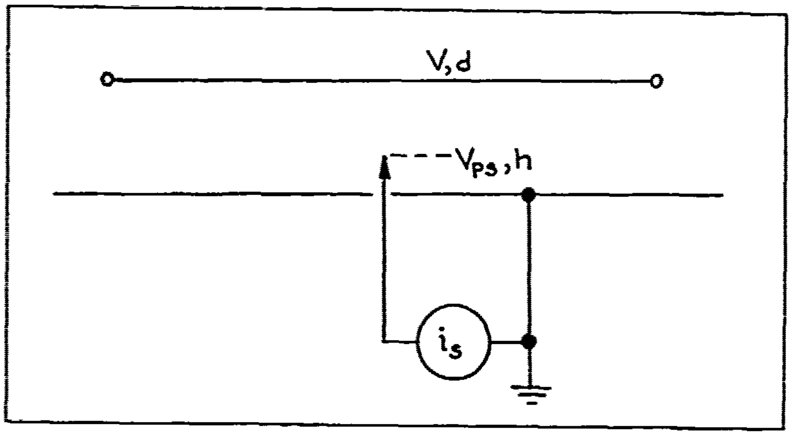


Fig. 3--The experimental arrangement for corona-discharge measurements using an electric field to simulate the effect of wind

From the analysis of the sphere and cylinder, we expect corona current from aircraft in flight to be proportional to the first power of the point potential and the wind speed. Thus the true current i_t from a corona point is

$$i_t = (V_{pt}/V_{ps})\,(v_t/v_s)\,i_s \quad (57)$$

where

V_{pt} = point potential on the aircraft

V_{ps} = simulated point potential, (56)

v_t = true airspeed

v_s = simulated wind speed

If we note that for actual corona points there is a starting potential V_0 of three or four kilovolts, (57) becomes

$$i_t \approx \left[\frac{V_{pt} - V_0}{Vh/d - V_0}\right] \left[\frac{v_t}{kV/d}\right] i_s \quad (58)$$

My colleague, Roland Pilié, has made careful measurements with an experimental arrangement like Figure 3. The lower plate was 0.81 meter in diameter; the upper plate was 0.61 meter in diameter and its circumferential edge was protected by a corona shield consisting of a bicycle tube painted with a conducting layer of colloidal graphite. The point was a Recoton Superchrome Phoneedle (a standard 0.006-cm radius, 78 rpm phonograph needle) placed at various heights h from 0.04 to 0.12 m above the lower plate. Plate separation d was 0.30 m. These data were taken in 1953.

Curves followed the usual quadratic form above a starting potential, as would be expected. For example if the analysis of equation (58) is correct, one would expect

$$i_s \propto hk(V - V_0')\,V/d^2 \quad (59)$$

where

$$V_0' = V_0\,d/h \quad (60)$$

Thus current would be quadratic with V above a starting potential V_o'.

Some representative data taken at 20°C and 74cm Hg pressure, with h = 0.10 m and d = 0.30 m, were

$$i_s = \pm 22.7 \times 10^{-6} \text{ amperes, } V = +64{,}500 \text{ volts or } -76{,}500 \text{ volts; and}$$

$$i_s = \text{zero at onset, } V_o' = +9000 \text{ volts or } -12{,}000 \text{ volts.}$$

Taking values of mobility as $k+ = 1.6 \times 10^{-4} m^2/\text{sec volt}$, and $k- = -2.2 \times 10^{-4} m^2/\text{sec volt}$, we can reduce the data to 0°C and 76cm Hg, and then normalize to $V_{pt} = 100{,}000$ volts and v = 100 m/sec, we have for the positive point (negative upper plate)

$$i_{t+} = +225 \times 10^{-6} \text{ amperes} \qquad (61)$$

and for the negative point (positive upper plate)

$$i_{t-} = -227 \times 10^{-6} \text{ amperes} \qquad (62)$$

In view of the fact that the simulated speed of (55) depends on mobility and on potential, it is interesting that the measured data give essentially equal currents. This independence of current upon mobility was referred to earlier. The simulated wind-speeds from (55) may be readily calculated to be 45 m/sec for the positive point, and 52 m/sec for the negative point.

Data of the type given here taken by various observers are not always in quantitative agreement. In one experiment [LANGMUIR, 1945] data were given for the negative point only where d was 0.05 m. Using that data, the negative point current would be about twice the current given here. It may be that in the smaller apparatus, all the electrons from the discharge had not attached to form negative ions. The near equality of the positive and negative currents using the data given here suggest that in these experiments ions rather than free electrons were involved.

If the simulation could be done with a strictly isolated point, it is the opinion of the author that the method would be quite good, in spite of possible electrical mirror image effects in the plate. The point, however, is supported mechanically with an electrical conductor, which to some extent distorts the field lower than the point. It is difficult to say whether this effect decreases the current by reducing the simulated wind behind (or lower than) the point, or whether it increases it by yielding a correspondingly greater field ahead of (or higher than) the point. Probably both effects would be fairly small, not exceeding ten per cent.

Miscellaneous comments--All the preceding analyses have involved approximations, and obviously the results must not be considered quantitatively precise. For example, we have considered a space charge sphere from which wind is excluded, with the wind having full speed elsewhere. Clearly this model can be only approximate, especially since the 'sphere' probably will be skew.

If the airplane is not aerodynamically clean with sharp trailing edges, there will be image forces in the airplane. A flat plate transverse to the wind and transparent to it (if such can be imagined) would reduce the current by a factor of about 2.

If there is a conducting plasma around the point, there will be little voltage drop for a short distance. Hence V_1 will apply to a surface having a radius r_1 of a few centimeters. The effect on the current is the same as increasing the point potential. This phenomenon was perhaps responsible for the fact that altitude chamber measurements of current [FELTON, and Others, 1953] quantitatively were greater than theory would call for on the basis of the chamber radius. A ratio of plasma radius to chamber radius of one to nine increases the current 2.25 times over that for a point.

It is worth noting that the starting potential for a high voltage flame is zero, but for a metal point it is a few thousand volts.

With an ordinary point, the discharge is very unsteady until the current reaches a value at least as great as about half a microampere. If radioactivity is applied to the corona point, then a finite stable discharge is obtained with a very low voltage. The corona point attached to the author's garage is 32 ft high, and has 320 micrograms of radium on it. In fair weather a current of 0.01 to 0.05 microampere commonly is obtained. With thunderstorms or snow squalls in the vicinity, the current commonly is one to five microamperes. Peaks as great as 20 microamperes of either polarity have been observed. The radioactivity is of negligible significance (other than in stabilizing the current) when the current exceeds about 0.3 microampere since the total ionization created by the radioactivity is of that order of magnitude.

If one attempts to establish a value for the surface potential of the space charge sphere by integrating the field from the narrow dense region of space charge from infinity, irrespective of the path the result is infinite. This shows that the broad region of space charge of opposite polarity should not be ignored in this type of integration.

When discharge currents are being measured in fair weather, it is important to note that performance data should be taken when the aircraft is zero-charged. Otherwise the potential of the aircraft may influence the discharge, so as to give misleading results. To obtain maximum current under zero-charge conditions, the aircraft should be charged (by manual over-ride on the controls) with one polarity. Then the discharge polarity should be changed, and current recorded as the aircraft passes through zero-charge.

Data and conclusions--It seems to be established that for this type of discharger configuration with an isolated high-voltage corona point, the current is proportional to the first powers of the point potential and the velocity, and is independent of mobility, and hence of polarity and altitude.

Unfortunately, the data [PELTON and Others, 1953] from the B-29 are very meager; in fact there is only one really useful current measurement at +23 kilovolts at a true airspeed of 273 miles/hour. The result is somewhat questionable and should not be considered as definitive. Adopting a four-kilovolt starting potential, and extrapolating to the normalized values of 100 kilovolts at 100 m/sec, the current would have been 154 microamperes. Aerodynamicists at the Laboratory [PELTON and Others, 1953] consider that the true airspeed in the vicinity of the point was between 0.6 and 0.8 of the true aircraft speed, since the special fairing at the tail surface built to accommodate the point somewhat shielded the point aerodynamically, and hence probably reduced the wind speed there. If we adopt an average value of 0.7 for the speed reduction factor, then at the full speed of 100 m/sec the current would have been 220 microamperes.

A summary of the magnitude of the currents we have discussed follows:

(a) Method of the simple space charge sphere	555 microamperes
(b) Method of the space charge sphere and cylinder	388 microamperes
(c) Method of the space charge sphere and paraboloid	394 microamperes
(d) Method of variation of f $f = 0.333/\ln 2 = 0.480$	197 microamperes
(e) Method of variation of f $r_2 = r_3$, therefore $f = 0.442$	245 microamperes
(f) Observation by simulation (1953 data of Pilie)	226 microamperes
(g) Other methods of calculation [CHAPMAN, 1955]	170-400 microamperes
(h) Extrapolation of the B-29 datum	220 microamperes

Method (a) obviously gives a value that is too large, and it should be rejected from serious consideration. Values of Methods (b) and (c) probably are distinctly too large. The reasoning relating to the variation of f suggests that the value of Method (d) is probably too small, with a preference for the value of Method (e). As remarked in discussing still air simulation, the result (f) is probably fairly good. Not a great deal of confidence can be attached to the measurement (h). In my own thinking I consider 225 ± 25 microamperes to be reasonable, on the basis of calculations and simulation.

The figures just given apply to the use of a single isolated point behind the aircraft, this point receiving full benefit of the slip stream. Clearly, if several well-separated points are used, the current should be proportional to the number of points. If points are not spaced considerably farther apart than twice the space charge sphere radius ($2r_2$ = about 40 cm at 18,000 ft altitude or about 20 cm at sea-level) then interference effects between points would be expected to reduce the current per point. The point must be placed behind the airframe skin a distance distinctly greater than r_2 if return current to the aircraft is to be avoided.

Acknowledgements--The following members of the Physics Department have made contributions to this work: Leonard Geller, Frank Pelton, Roy W. Hendrick, H. T. McAdams, Roland J. Pilié, and George Richmond. Most of my own effort on this paper was out-of-hours, but it seems appropriate to note that both the U. S. Navy and U. S. Air Force have supported projects in atmospheric physics at Cornell Aeronautical Laboratory, and hence have helped to maintain my interest in problems related to the one discussed in this paper.

References

CHALMERS, J. ALAN, Atmospheric electricity, Oxford Univ. Press, London, 1949.

CHALMERS, J. ALAN, Atmospheric electricity, Rep. Progress in Physics, v. 17, pp. 101-134, 1954.

CHAPMAN, SEVILLE, Discharge of corona current from points on aircraft or on the ground, Cornell Aeronautical Lab. Rep. 66, 64 pp., 1955.

GREEN, JULIUS, and G. J. LAURENT, Final engineering report on precipitation static reduction, Research Div., Philco Corp., Contract USAF W33-038-ac-20763, 135 pp., February 9, 1950.

GUNN, R., and Others, Army-Navy Precipitation-Static Project, Proc. Inst. Radio Eng., v. 34, pp. 156-177, and pp. 234-254, 1946.

LANGMUIR, I., Final report on investigation of fundamental phenomena of precipitation static, General Electric Co., Contract W-33-106-sc-65, 60 pp., October 1943-May 1945.

LOEB, L. B., Recent developments in analysis of mechanisms of positive and negative coronas in air, J. Appl. Phys., v. 19, pp. 882-897, 1948.

PELTON, FRANK, and Others, Investigation of means to maintain zero electrostatic charge on aircraft, Final report RA-766-P-10, Cornell Aeronautical Lab., Contract AF 19(122)475, October 31, 1953.

REPORT ON SOME OBSERVATIONS ON ATMOSPHERIC ELECTRICITY

Josef Fuchs

Ramperstorffergasse 2
Vienna 55, Austria

Abstract--The audio-frequency phenomenon of 'whistlers' or 'sifflements,' which can be heard in long wires as a musical tone descending in frequency from several kilocycles to nearly zero cycles within an interval of about one second, was observed at the Sonnblick Observatory (elevation 10,200 ft) continuously over a six-year period. It shows a daily and a yearly fluctuation (Trabert; Conrad). Studies of potential-gradient measurements made during times of disturbed weather have shown distinct characteristics associated with the passage of different types of meteorological fronts. The form of the potential-gradient curve as a function of time during the passage of cold fronts is quite unique and easy to distinguish from that during the passage of warm fronts (Seper). Observations of the kind of atmospherics called 'grinders' and 'clicks' have shown that the former, probably resulting from glow discharges, exist only during the earlier phases of the development of a thunderstorm, while the latter, resulting from normal lightning flashes, predominate during the storm's main phase and thereafter. Continuous observations of grinders and clicks are therefore a valuable source of information about the electrical state of weather situations and also give indications about the dynamic processes envolved.

I should like to report some observations on atmospheric electricity, which may be of some value for a deeper understanding of problems, which are at present only partially solved.

The first report concerns the audio frequency phenomenon of 'whistlers' (or, in French, 'sifflements') which are of actual interest, because new hypothesis are made about their origin. Such a whistler can be heard easily in long wires as a musical tone, which descends in frequency from several kilocycles to nearly zero cycles in about 0.1 to 0.8 second.

I think that it will be of interest to note that this phenomenon was observed as early as 1883, and continuously during the six following years at the Sonnblick High altitude Observatory. This meteorological observatory is situated 3100 m above sea-level and is connected with the post office by a long and free telephone line in a north-south direction.

This telephone wire has a length of 22 km and covers a difference of elevation of more than two km. It was grounded at both ends. Immediately after completion, Professor Pernter often observed a whistle of variable intensity in the line and Professor Trabert evaluated the observations of the aforementioned six years. Later, in 1902, Professor Conrad, now in this country, made a special investigation on the intensity of these whistlers during cloudless weather and found a strong relation to the value of the normal daily periodically changing potential gradient of positive sign.

In 1928 I also observed this phenomenon as a short whistle of decreasing musical frequency, lasting about 0.2 second, with irregular intervals between two whistlers often up to several seconds. This phenomenon sounds, somewhat similar to the whistle produced by a flick with a whip. It was always perceptible without any amplifier. Furthermore I found that increasing values of the positive potential gradient are connected with an increasing number of whistlers to four or five per second. But, an interesting fact, this correlation failed at negative values of the gradient that is during disturbed weather. In this cases whistlers remaines weak, not withstanding that the negative potential gradient rose to values higher than -1000 V/m.

Figure 1 shows the normal daily period of the whistlers deduced by Trabert from the six-year series of observations from 1888 to 1894. One sees that the whistlers in the 22-km long telephone line show a regular behavior. The 0 means no whistlers, 1 means few, 2 medium, and 3 means a great number of whistlers.

Concluding this report on whistlers in long wires it can be said, that the Sonnblick observations did not lead to any conclusions about the physical cause of the phenomenon, but one gets the impression, that the electric field of the atmosphere must play a particular part in the generation of this phenomenon.

The second part of this report concerns the relation between the behavior of the potential gradient and the corresponding weather situation. It is known that the potential gradient often varies in close connection with the changing weather, but it is seldom possible to coordinate certain weather situations to certain states of atmospheric electricity. Because it was expected that the same meteorological situations must normally lead to the same distribution of charges in the interior of the clouds, a research program was undertaken with the aim of correlating the form of the curve of the potential gradient to the corresponding of weatherfronts.

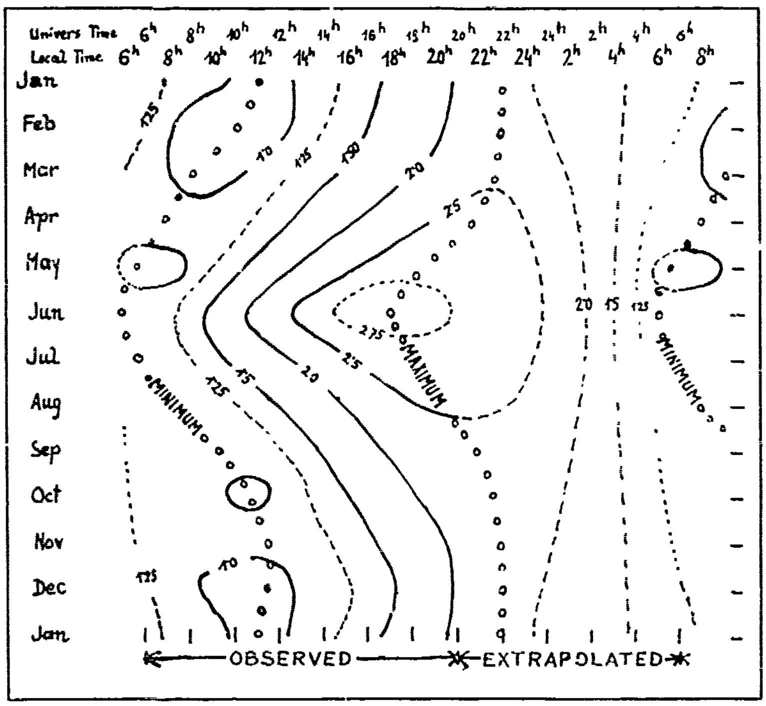


Fig. 1--The normal daily period of whistlers, deduced by Trabert from the six-year series of observation 1888-1894 at Sonnblick High Altitude Observatory, Austria

It was then observed by Dr. Seper (Fig. 2) that a normal warmfront produces in general a negative potential gradient during the whole time of its passage. Only when the front had passed, the field changed again to its normal positive values. Slow wandering cold fronts, such as those of the first order in the classification of Bergeron, behave nearly in the same manner. This is not surprising, for in both cases there is a warm air mass, which is gliding up on a cold air mass. The difference is only that in the case of a warmfront the active one is the warm air mass, whereas in the case of a cold front of the first order the active one is the cold air mass.

The observations showed also (Fig. 2) that the time of the passage of the front is more precisely determinable by means of the times of commencements of field changes than by that of the meteorological elements, observed on the ground.

A cold front of the second order in the sense of Bergeron shows quite another behavior. This is the well-known cold front of strong turbulence. In this case the field changes frequently between greater positive and greater negative values of the potential gradient. This behavior is easily understood for it is not only known, that the clouds of such a cold front have a complicated structure but also, that they must have a cellular and subcellular structure as, in an extreme case, is shown by the clouds of a thunderstorm.

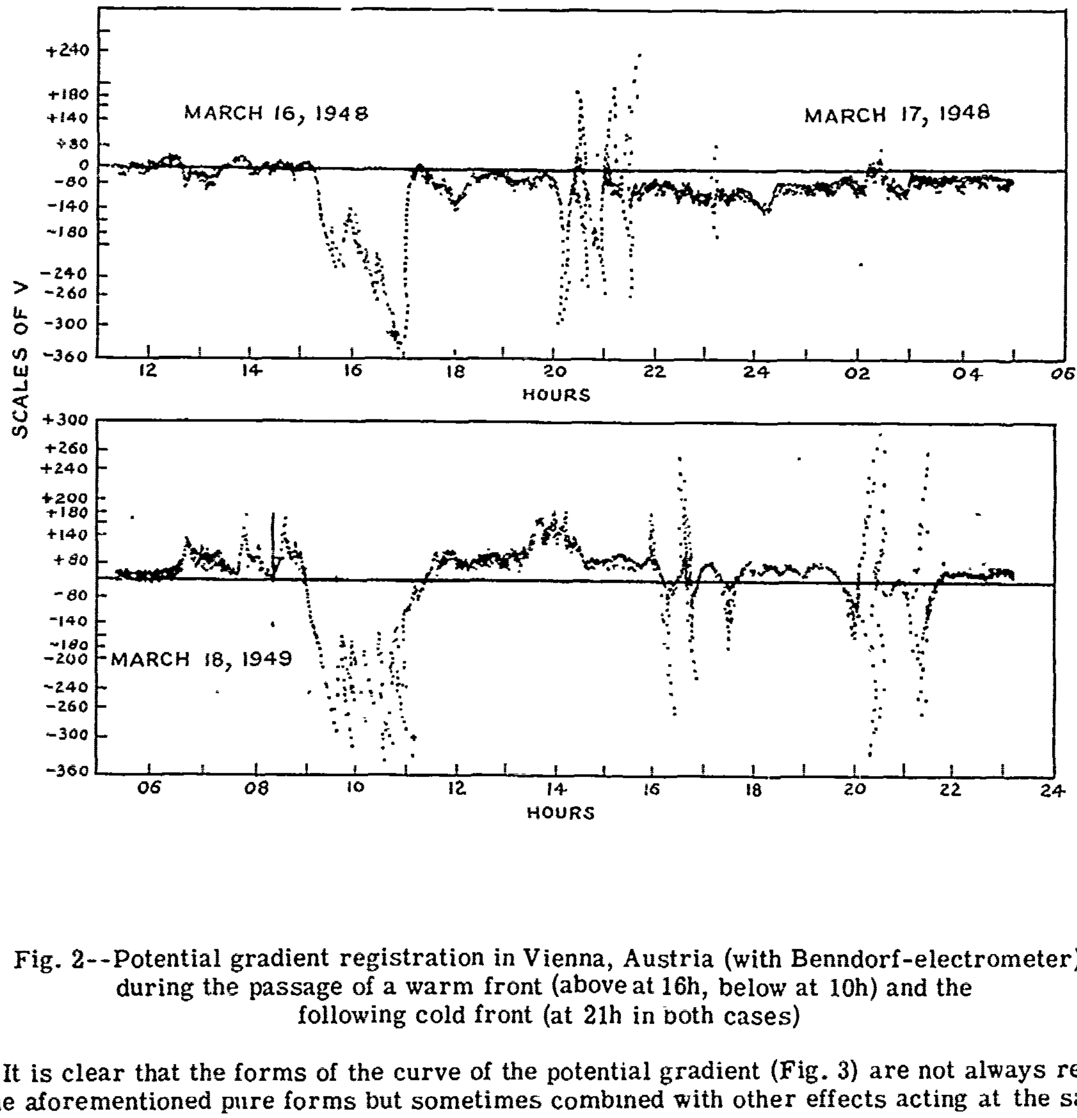


Fig. 2--Potential gradient registration in Vienna, Austria (with Benndorf-electrometer) during the passage of a warm front (above at 16h, below at 10h) and the following cold front (at 21h in both cases)

It is clear that the forms of the curve of the potential gradient (Fig. 3) are not always received in the aforementioned pure forms but sometimes combined with other effects acting at the same time.

The results of this investigation have shown that in every case the observation of the potential gradient gives a better knowledge of the dynamic events in a front than the observation of the meteorological elements on the ground.

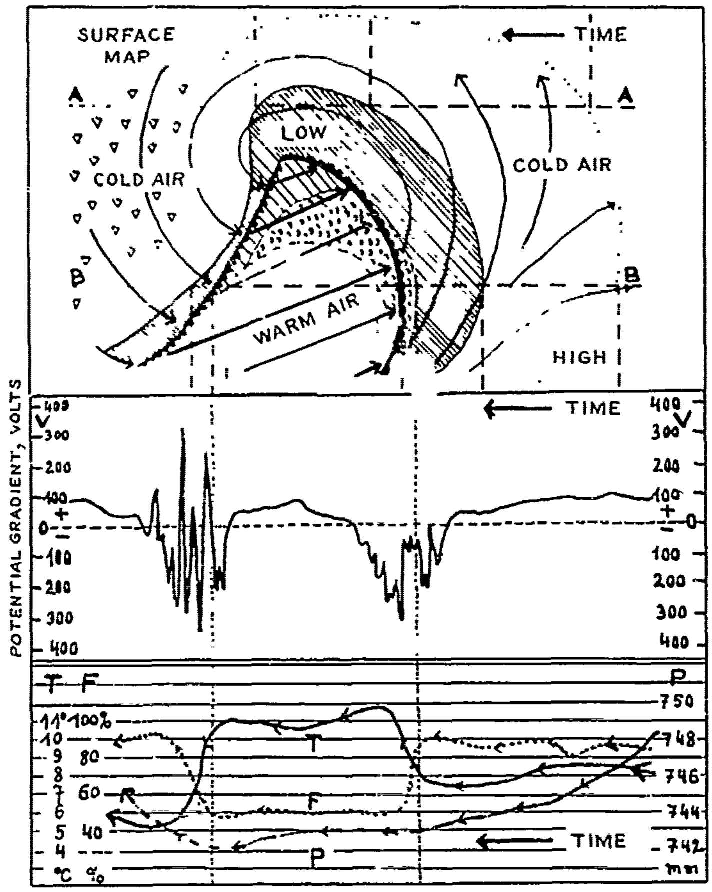


Fig. 3--The behavior (of an average of nearly 100 front passages) of the potential gradient during the passage of corresponding phases of a barometric depression; P = pressure; T = temperature; F = humidity

The third part of my short report concerns the qualification of two sorts of atmospherics to estimate the electric and dynamic status of clouds in the growth-stage and mature-stage of a thunderstorm. These two sorts are the 'clicks' and the 'grinders,' of which by far the greatest number of publications deals with the clicks.

The reasons are first that the receiver or any automatic device cannot distinguish between clicks and grinders, and second, that the clicks show on the average greater amplitudes than the grinders. Therefore nearly all automatic observations record clicks.

It is therefore necessary to observe atmospherics by ear, if one desires to distinguish between clicks and grinders. Careful investigations undertaken in this manner at the Sonnblick Observatory showed, that the causes of clicks and grinders are very different ones: Whereas (it is well known that) a click is generated mainly by the return stroke in the channel of a lightning discharge, the grinders originate at quite another phase of the electrifying process of a cloud.

There are two main observational facts concerning the appearance of grinders: (1) As soon as cumulus clouds are visible, grinders show a regular period, starting at noon, with a maximum during afternoon. (2) During times of thunderstorm activity and therefore strong click intensity, grinders often disappear completely.

As grinders like clicks are representative of the electromagnetic radiation of electric discharges in clouds, it was now necessary to ask for the cause of the suppression of the grinder-producing process, when the click-producing process begins to work.

Such a behavior is to be understood if there exists in normal cumulus clouds a charge separating process, which is restricted only to the upper parts of the cloud.

The proof about existence and location of such a process was delivered by the visual observation of a series of distant sheet lightning seen from the Sonnblick observatory as well as from the Solar Altitude Observatory Kanzelhöhe. Sheet-lightning was situated precisely in the growing top of a cumulo-nimbus-cloud, flashing up there with nearly regular intervals of three seconds. In all of these cases strong grinders could be observed in radio receivers.

About the basic physical processes the following can be said: It is known, that sheet-lightning is produced by glow-discharges. Because of the reduced pressure in these heights, discharges occur there at lower fields and therefore with reduced charges. No normal flash can be produced there.

The difference between the strong grinders accompanying sheet lightning, and the weak grinders observed during the presence of normal cumulus clouds, is only a quantitative one. In the last case the grinders are produced in the turbulent upper parts of normal cumulus clouds by much weaker and therefore invisible glow-discharges: they can also be called micro-flashes. The range of the weak electromagnetic radiation of this kind of discharge may not exceed 20 km.

The mechanism of the separation of charges at these heights of low pressure for the generation of normal grinders may be of the same kind as proposed for the separation of charges in clouds, that is, based upon electrification resulting from the freezing of supercooled droplets and the other connected necessary mechanisms in the turbulent parts of the clouds.

The aforementioned restriction of the electrification processes to the top parts of cumulus clouds is caused by meteorological circumstances alone, because the greatest turbulence is located there during the cumulus stage. Only when a cumulus becomes able to extend its inner turbulence to lower levels, that is with the beginning of the downward air-current, then the cloud as a whole will be included in the electrification process. This signifies the change from the cumulus stage to the mature stage.

The top part of the cloud then loses its individuality as an electric generator and remains only a part of a much greater one. The disappearance of grinders, due to the ceasing of glow-discharges in very high levels and the appearance of clicks, caused by the newly formed normal flashes in lower levels, characterizes this stage.

The correct discrimination between clicks and grinders is therefore a means to determine from moment to moment whether the cloud as a whole or only the top-part of it is acting as a generator of electricity.

EFFECTS OF RADIOACTIVE DEBRIS FROM NUCLEAR EXPLOSIONS ON THE ELECTRICAL CONDUCTIVITY OF THE LOWER ATMOSPHERE

D. Lee Harris

U. S. Weather Bureau
Washington, D. C.

Abstract--An increase in the ionization near the ground due to the fall out from a radioactive cloud formed by a nuclear explosion will increase the conductivity and lower the potential gradient in the lower atmosphere. Records of atmospheric conductivity and potential gradient from the Tucson Magnetic Observatory are compared with records of the deposition of atomic debris on the ground following the Nevada tests. The observed changes are not inconsistent with values computed from theoretical considerations. Most of the effects are confined to a very shallow layer, within a few meters of the ground.

It has been suggested on several occasions that the ionization produced by the debris from the atomic bomb tests in Nevada might produce significant changes in the normal electrical parameters of the lower atmosphere on either a local or world-wide scale. Recently, the Scientific Services Division of the Weather Bureau decided to investigate the magnitude of these changes.

The Weather Bureau, in cooperation with the Atomic Energy Commission, has maintained a network of observation stations to measure the spread of radioactive debris across the country after each of the last several atomic test series. An estimate of the debris deposited on the ground is obtained by exposing one-foot square sheets of gummed paper on a horizontal stand about 30 inches above the ground at a large number of stations scattered throughout the country. These papers are exposed for a 24-hour period, and are sent to the New York Operations Office of the Atomic Energy Commission for a count of the radioactivity. In most cases, two or three papers were exposed simultaneously. In general, the simultaneously exposed papers at any one station showed good agreement, but differences of an order of magnitude were observed in a few cases. A description of these observations has been given by U. S. ATOMIC ENERGY COMMISSION [1953], EISENBUD and HARLEY [1953], and LIST [in press].

The Tucson Magnetic Observatory, at Tucson, Arizona, makes continuous measurements of the positive and negative conductivity as well as the potential gradient. These instruments have been described in detail by TORRESON [1939] and by WAIT and PARKINSON [1953]. The following brief description will be sufficient for the present purposes. A schematic diagram of the Observatory, a flat-roofed structure three meters high, is given in Figure 1. The potential gradient is measured by a radioactive probe extending outward from one wall at a height of 2.45 m above the ground. Both positive and negative conductivities are measured by means of modified Gerdien apparatus. The air is drawn into the instrument through vent pipes on the roof and is exhausted under the floor of the building by means of a fan at floor level. According to Torreson, the air is drawn through the system at a velocity not less than two meters per second.

Fortunately Tucson is in the network of stations which record the fall out of atomic debris, and so it is possible to make a reasonably direct comparison of these two sets of records. Although Tucson is near the Nevada test site, the winds from the proving grounds generally pass north of Tucson, and only a few cases of significant fall out have occurred. The greatest fall out recorded at this station was measured from the gummed paper exposed between 11h 30m MST, June 2 and 11h 30m MST, June 3, 1952. In this case, three papers were exposed, and they showed good agreement, indicating a fairly homogenous fall out. A tracing of the records of atmospheric conductivity and potential gradient corresponding to this period is given in Figure 2. The record prior to 21h 00m

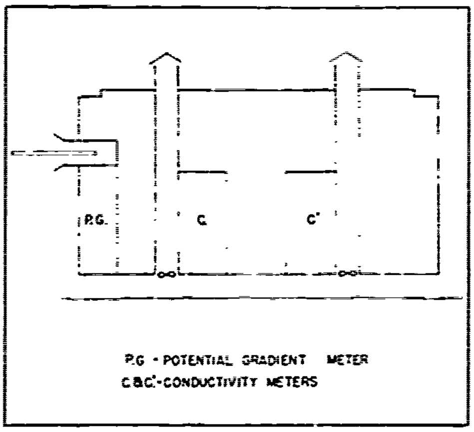


Fig. 1--Schematic diagram of the atmospheric electricity observatory, Tucson, Arizona; P. G.-potential gradient meter; c, c′, conductivity meters

is typical of that recorded for several days prior to that time. The record after 24h 00m is typical of that recorded for the next four or five days.

The hourly mean values of the potential gradient and conductivity for the period 08h 00m June 1 to 08h 00m June 5 are shown in Figure 3. Since the calibration factors necessary to reduce these observations to absolute units over the range of values observed are not available, the deflections of the instrumental records from the zero values are shown in arbitrary units. The smooth lines drawn on the right-hand portion of the conductivity records represent the theoretical conductivity due to both natural causes and fission products based on certain assumptions to be discussed below.

There were several thundershowers at Tucson on June 2 and the abrupt change in the character of the record occurred at the end of the last shower. A study of the upper winds indicates that only a

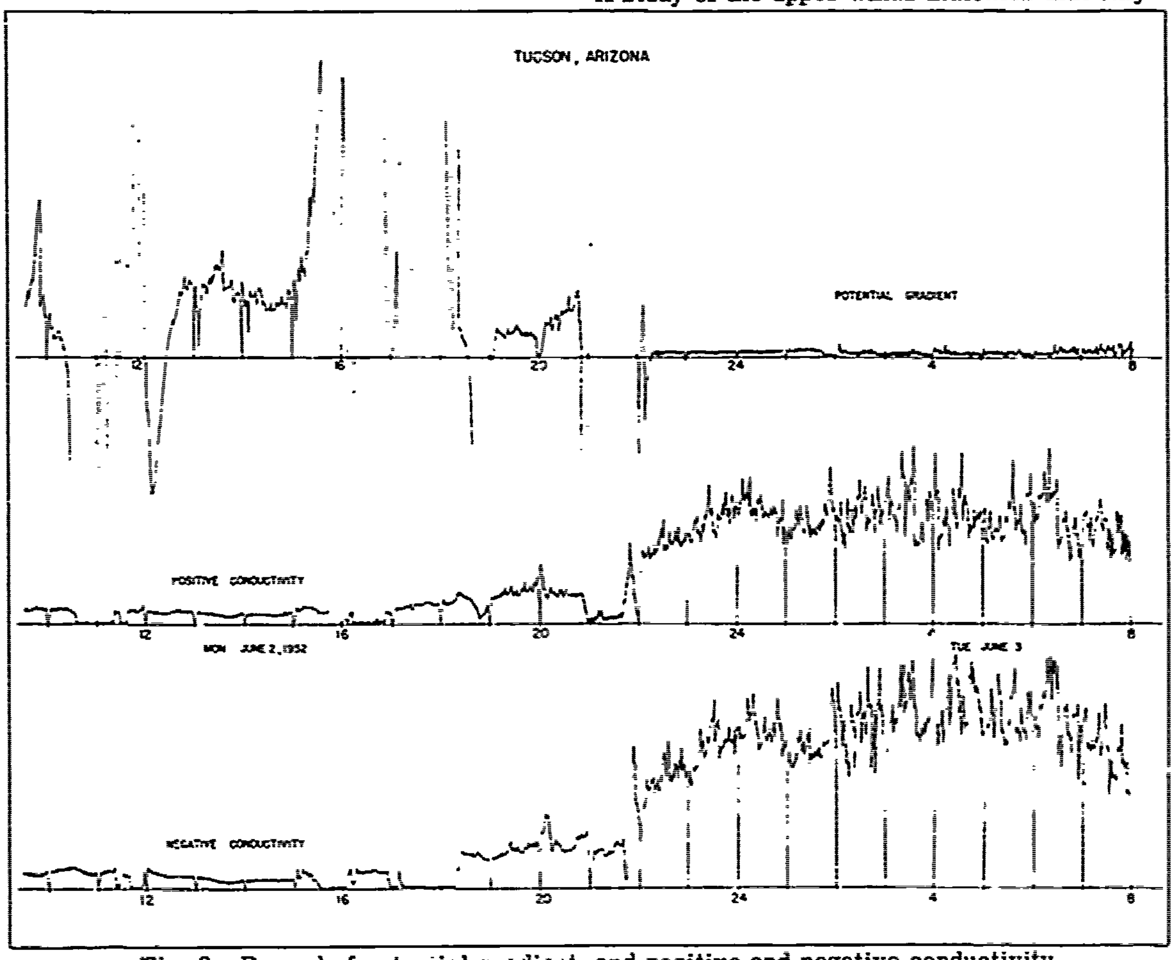


Fig. 2--Record of potential gradient, and positive and negative conductivity, June 2-3, 1952 at Tucson

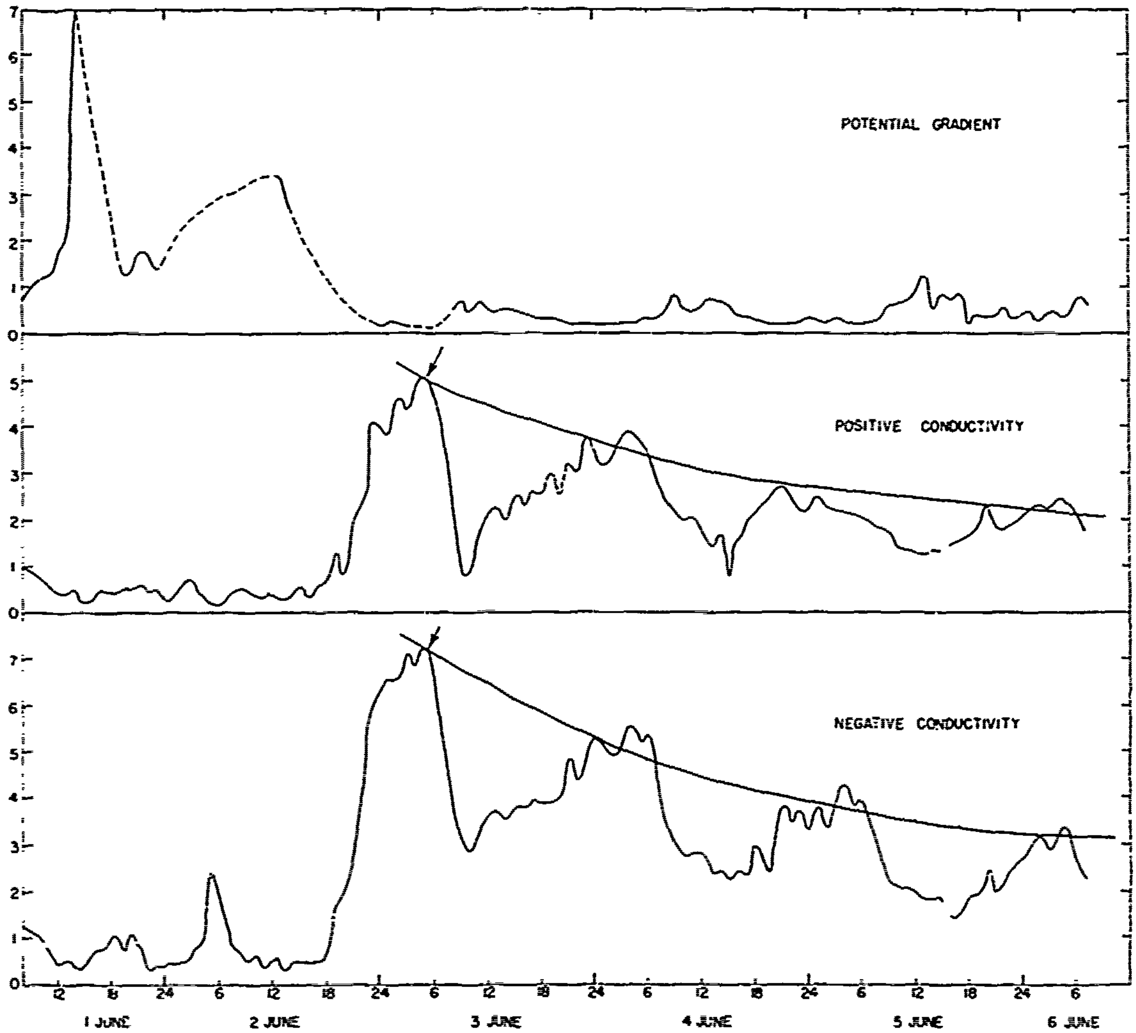


Fig. 3--Record of potential gradient, and positive and negative conductivity, June 1-6, 1952 at Tucson

thin portion of the radioactive cloud passed over Tucson at an altitude of about 16,000 ft. The available data indicate that this debris must have been carried downward by the last shower of the day.

The conductivity appears to have been increased about tenfold and the potential gradient when not affected by the showers, appears to have been decreased by a factor of about six following this fall out. The observer's log indicates that he investigated every likely source of instrumental failure without learning the cause of the unusual disturbance in the record. The records of both conductivity and potential gradient were clearly abnormal for four or five days following this fall out. The conductivity record appears to have been somewhat abnormal for a longer period, but the values observed were within the range of natural variability.

It is interesting to compare the recorded change in conductivity and potential gradient with theoretical calculations. According to the U. S. ATOMIC ENERGY COMMISSION [1950] the fission products are primarily beta and gamma emitters. The average maximum energy of the beta particles

is 1.3 Mev, but most of the particles have smaller energies so that the over-all mean is about 0.4 Mev. The range of a beta particle in air is a little less than five meters for a particle of 1.3 Mev energy and less than 0.75 meter for 0.4 Mev particles. Since the beta particles are being continuously deflected by electrons and nuclei of the atoms in the air, they follow very tortuous paths, and the effective range in a straight line is very much less than that indicated above. The average energy of the gamma radiation from fission products is about 0.7 Mev. The gamma rays do not have a definite range, but their intensity decreases about an order of magnitude by passing through 240 m (788 ft) of air. It is assumed that the source is an infinite plane.

On the average 33.2 electron-volts will be consumed in the production of each ion pair. Thus, the average beta particle will produce 1.2×10^4 ion pairs, and most of these will be produced within 50 centimeters of the source. The U. S. ATOMIC ENERGY COMMISSION [1950] gives graphs relating the contamination at the ground in terms of megacuries per square mile to roentgens of gamma radiation per hour as a function of height above the ground and the initial energy. By making the proper conversions it can be shown that one disintegration per minute per square foot will produce about 2.9×10^{-5} ion pairs per cc per second, at an elevation of one meter above the ground.

The fall out observed at Tucson in this case was about 4×10^5 disintegrations per square foot per minute on the day of fall out. Thus the gamma rays would have produced about 11.5 ion pairs per cc per second in the lowest few meters, or just a few more than are normally produced by natural processes. The total ion production due to gamma rays from fission products and the average natural production does not exceed the largest values of the natural production which are commonly observed near the surface over land. However, the beta particles would have produced approximately 4.8×10^9 ion pairs per minute per square foot. If these were all produced in the lowest 50 centimeters above the ground, this would amount to an average production of 1.7×10^3 ion pairs per cc per second.

The true relation between ion production and conductivity for these conditions is not known. However, we can make an estimate of the relation by consideration of the simple expression for equilibrium conditions

$$q = \alpha n^2 + \beta n \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad (1)$$

where q is the number of ion pairs produced per cc per second, α is the recombination coefficient for small ions, n is the number of small ions per cc, and β is a complex factor which is a function of the number of large ions and natural condensation nuclei present. It is assumed that conductivity is proportional to n.

The value of beta pertaining to this problem is not known with sufficient accuracy to permit an exact evaluation of the effect of the above ionization on the conductivity. However, it may be safely assumed that conduction will not increase faster than the ionization. For very large values of q, such as may prevail in the region in which beta particles are most effective, we may expect conductivity to approach $(q/\alpha)^{0.5}$, and may be even less than this value because of the ions lost by vertical diffusion. The ions produced by beta particles cannot effect a every deep layer of the atmosphere, for their source region is the lowest few centimeters of the atmosphere and as they diffuse upward there will be an excess above the equilibrium ion density and recombination will be very rapid. STERGIS [1954] has shown that under such conditions the ion density in the non-equilibrium system may decrease by an order of magnitude within the first minute away from the source region and equilibrium conditions will normally be reached within five to 15 minutes.

The increase in conductivity at Tucson, which cannot be explained by the ions produced by gamma rays, is probably due to the diffusion of the ions produced by the beta particles. Since the ion concentration decreases rapidly in any particle of air which leaves the source region, it is believed that any increase in conductivity due to ions produced by beta particles from atomic debris on the ground would be greatest during the day when vertical mixing is greatest. However, the highest

values of conductivity are found in the early morning hours, when it is unlikely that the vertical mixing could lift the ions produced near the ground rapidly enough to account for the increased conductivity.

Since the observatory has a flat roof, it is likely that much of the original radioactive material which fell on the roof remained there. If we assume that the increase in conductivity is due mainly to the beta particles from radioactive material on the roof, it becomes easy to account for the recorded changes in conductivity, and for the fact that the change in the potential gradient, which depends largely on the conductivity through a layer of 2.5 m, is less than that which would be expected from the recorded change in conductivity.

If the above interpretation is correct, the conductivity will be sharply stratified in the lowest few meters. At night, when the local turbulence is at a minimum the air sampled by the Gerdien apparatus will consist largely of air which has been ionized by the beta particles from the debris on the roof of the observatory. During the day, there will be more mixing with air which has been over the roof a shorter period of time, and the conductivity would be expected to drop. The addition of more condensation nuclei from the ground would also lead to a decrease in conductivity during the day time. It appears that the actual conductivity should be expected to conform to the theoretical value more closely during the night than during the day. The theoretical curve shown in Figure 3, was fitted at the time of the first maximum of conductivity. This computation is based on the assumptions that the response of the conductivity recording instrument is linear; the total conductivity may be expressed as the sum of an average value due to natural causes and an additive term due to ionization by fission products; and conductivity is proportional to ionization. That is to say, it is assumed that

$$\lambda = \bar{\lambda} + \lambda_\beta t^{-1.2} \quad \ldots \ldots \ldots \ldots \quad (2)$$

where $\bar{\lambda}$ is the average conductivity for each 24 hour period just preceeding the fall out; λ_β is a constant determined by the data, and t is measured in hours after the explosion.

In this case it appears that most of the change in conductivity is due to the beta particles which originate within a meter or so of the measuring instrument. It is doubtful if the conductivity or the electric field would be significantly modified at any great distance from the ground. Some confirmation for this point of view is provided by Figure 4, which was furnished by W. D. Parkinson of Fordham University. The continuous line represents the ion production at 12 cm above an iron plate exposed above a flat roof at Fordham University. The circled dots and crosses indicate the conductivity measured by a Gerdien apparatus about four feet above the roof of a six story building at Mt. St. Vincent College in New York City. Each point represents the average conductivity for a twelve hour period. It is noted that the ion production at 12 cm above the plate on March 19 is about ten times the natural ion production, yet the average conductivity is increased by a factor of less than two. The increased ion production and conductivity on March 19, is due to a radioactive fall out from the atomic bomb detonated on March 17.

The next highest fall out at Tucson was about an order of magnitude less than the one discussed here, and occurred on April 19, 1952. There is no clear-cut evidence that the artificial radioactivity due to atomic bombs affected the electrical records at Tucson on this date or at any other time aside from the above mentioned case.

The General Electric Research Laboratory maintains a corona discharge current meter at Schenectady, New York. This instrument has been described by FALCONER [1949, 1953] and by Schaefer elsewhere in this volume. The records from this instrument have been compared with the fall out values observed at the Albany airport a few miles from Schenectady.

The Albany records show only one fall out of the magnitude of that discussed above. This occurred between 07h 30m EST April 26 and 07h 30m EST April 27, 1953, and was about 40 times greater than that at Tucson. The discharge current dropped sharply during this period and the fair weather field

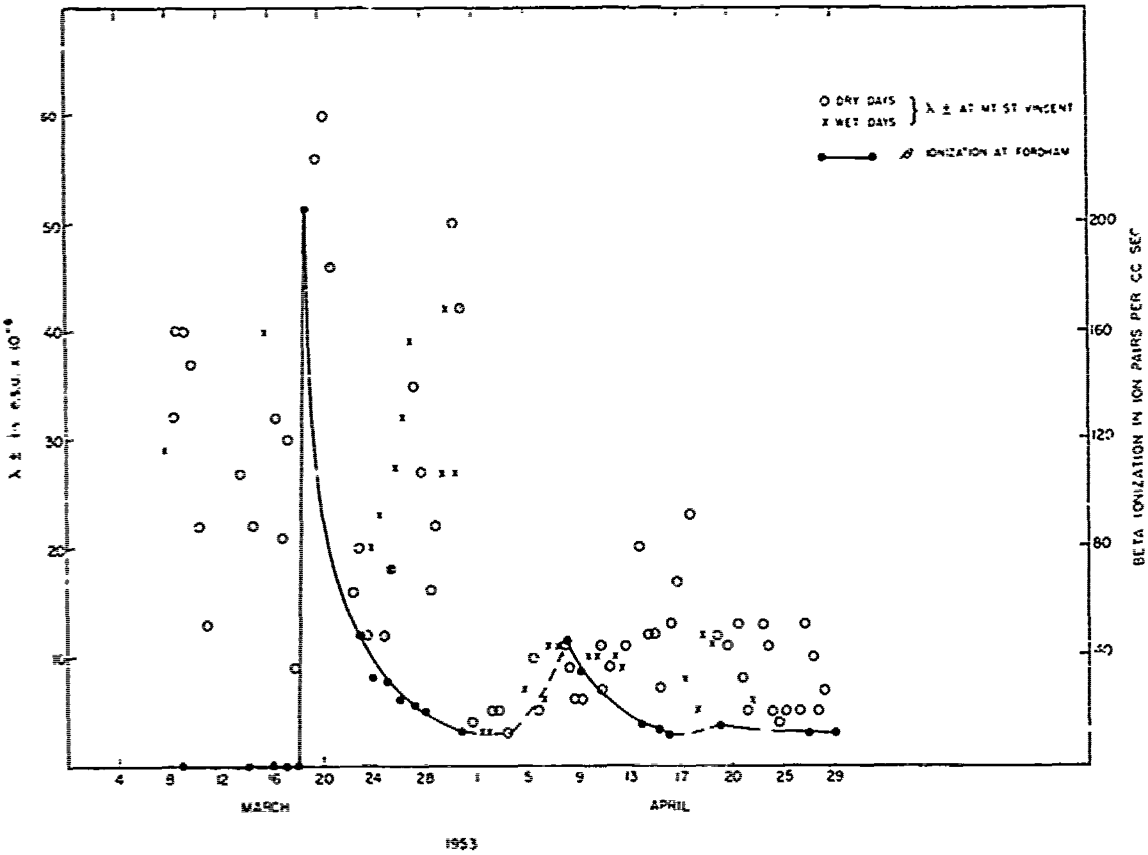


Fig. 4--Record of conductivity and beta ray ionization at New York, N. Y., March and April, 1953

remained about an order of magnitude below normal for several days. However, this instrument is not a satisfactory device for detecting the presence of radioactive debris. The records for all periods during which atomic weapons were being tested were examined by Falconer to determine if there were other periods in which the records of discharge current were similar to those observed following April 26. Other periods with similar records were found in which there was little likelihood that bomb debris might be involved. In one case, April 1-10, 1952 the period of low discharge current began a few hours before the bomb was detonated and several days before any artificial radioactivity was observed at Albany.

Radioactive fall out of the magnitude of that discussed for Tucson have occurred in some parts of the United States during each of the last three test series at the Nevada Proving Grounds, but not following each individual test. Fall out of ten times this value has occurred over some part of the United States on several occasions. The largest single measurement of fall out more than 300 mi from the test site was 40 times as great as that discussed above. It is to be expected that surface measurements of the atmospheric electrical parameters made within a few days following a fall out of this magnitude will be significantly altered by this artificial radioactivity. No evidence has been found which would indicate that changes in the electrical parameters of the magnitude discussed above will have a measurable effect on the weather.

Acknowledgments--I wish to express my appreciation to the Carnegie Institution of Washington for lending the records of the Tucson Observatory, to Raymond Falconer and the General Electric

Company for the use of the Schenectady records and to W. D. Parkinson for providing me with the data shown in Figure 4 and for several helpful comments during the preparation of the final manuscript.

References

EISENBUD, MERRIL, and JOHN H. HARLEY, Radioactive dust from nuclear detonations, Science, v. 117, pp. 141-147, 1953.

FALCONER, RAYMOND E., Some correlations between variations in the atmospheric potential gradient at Schenectady and certain meteorological phenomena, Project Cirrus Occ. Rep. 18, G. E. Research Lab., Report RL-287, 1949.

FALCONER, RAYMOND E., A correlation between atmospehric electrical activity and the jet stream. Final Report ONR Project, G. E. Lab., Rep. RL-1007, 1953

LIST, ROBERT J., Transport of Atomic debris, Bull. Amer. Met. Soc., v. 35, pp. 315-325, 1954.

STERGIS, C. G., Study of atmospheric ions in a non-equilibrium system, J. Geophys. Res., v. 59, pp. 63-66, 1954.

TORRESON, O. W., Instruments used in observations of atmospheric electricity, in Physics of the Earth, v. 8, Terrestrial Magnetism and Electricity (J. A. Fleming, ed.), McGraw-Hill, pp. 231-269; 1939.

U. S. ATOMIC ENERGY COMMISSION, The effects of Atomic weapons, U. S. Gov. Print. Office; 1950.

U. S. ATOMIC ENERGY COMMISSION, Assuring public safety in continental weapons tests, U. S. Gov. Print. Office, 1953.

WAIT, G. R., and W. D. PARKINSON, Appendix to investigation of electrical properties of the atmosphere, Dept. Terr. Mag., Carnegie Institution of Washington, 1953.

DISCUSSION
CONCERNING THE PAPERS PRESENTED ON THE MORNING OF MAY 20, 1954 AND RELATED ATMOSPHERIC ELECTRICAL PHENOMENA

J. A. Chalmers presiding

Dr. Chalmers--We will start off with the discussion on the various points on the air-earth current that came up in the earlier parts of this morning's papers. Who will start the ball rolling on the question of the convection current that was mentioned.

Dr. Swann--It should be pointed out that if one makes measurements by a process in which the 'collecting disc' is covered with a shield, then exposed, and then covered again, the charge collected is a true measure of the conduction current. If the disc is left exposed continually, we get additional effects due to the convection currents, and by making both kinds of observations we can separate the effects.

Dr. Holzer--The pattern of measurement that we are using, is essentially similar to that suggested by Dr. Swann. We are measuring simultaneously the potential gradient, both polar conductivities and the air-earth current, not by the shielding method, but by a method similar to that described by Dr. Kasemir. I believe a comparison of the direct and indirect measurements should do essentially what Dr. Swann suggests.

Dr. Chalmers--You are in fact measuring it directly and indirectly.

Dr. Holzer--Yes. The direct measurement is more nearly like the method Dr. Kasemir described than the C. T. R. Wilson procedure which Dr. Swann described.

Dr. Chalmers--Dr. Kasemir, you had some point on the sunrise effect?

Dr. Kasemir--As a result of 20 days measurement at Aachen, we, like Dr. Holzer have noticed a sunrise effect. When data from the best fair-weather days are selected with no wind or cloud, and averaged, we find that the potential gradient begins to increase at the time the Sun comes over the horizon. There is no important corresponding change in conductivity. During the first two hours after sunrise the gradient doubles in value. These observations suggest a change in columnar resistance or the development of a source of electromotive force.

Dr. Holzer--It is interesting to note that the difference in longitude between Aachen and California makes the effect more difficult to detect in the latter case. Sunrise at Aachen occurs when the world-time curve is near a minimum while sunrise in California occurs when the world-time curve is rising. For this reason we observe the sunrise effect as a change in slope. A change in columnar resistance or the development of a source of electromotive force are the possibilities that must be examined as a physical cause. I think these questions will be decided by experiment.

Dr. Chalmers--Is there any contribution on that point before we pass to the next?

Dr. Israël--I should like to ask Dr. Holzer about the problem of the separation of convection and conduction current. From my earlier experience I found that my computed values of air-earth conduction current did not agree with the directly measured value. There were seasonal variations from winter to summer and the amplitude of the variation of the computed values is greater than that for the measured values.

Dr. Holzer--Most of our air-earth current values have been based upon the product of measured potential gradient and measured conductivity, and because we have not obtained an extensive series of direct measurements, I would be reluctant to try to generalize on the data we have.

However, we do hope this summer (1954) to get enough measurements to make a more definitive statement on this problem in California and Hawaii.

Dr. Chalmers--Do we have anything more on the subject?

Dr. Israël--As Dr Holzer spoke this morning of the two effects, world-wide and local, we have tried to separate these effects by measurements at a single station.

Using the measurements at the Jungfraujoch, I tried to separate the two effects by comparing the potential gradient and the directly measured air-earth current. During the summer the diurnal curves of the two parameters differ, whereas in the autumn the diurnal curves are parallel. The difference in the two seasons is caused by the fact that the austausch layer effects the mountain tops in summer but not in the autumn.

Dr. Holzer--I think that the only difference that may exist between Professor Israël's position and mine is a slight difference in point of view. Professor Israël has inferred from three measurements at a single station that he has measured the world-wide effect, and I am inclined to believe that Professor Israël's inference is correct because of the stability of his conductivity.

However, I think that the final proof of this must depend upon two station measurements. Because of the great complexity of this problem, one must first obtain stations at which the local effects are small or calculable. After one has obtained two such stations at different longitudes so that no local diurnal effects can be in phase, parallel records from the two stations are proof that one is measuring a world-wide effect. It is possible that even for the best mountain stations, proportional air-earth current measurements will be obtained only during the dark hours.

Dr. Chalmers--Dr. Byers has a comment on the situation of Dr. Holzer's stations.

Dr. Byers--The region of Prof. Holzer's measurements is one of the most 'quiet' in the world, from a meteorological climatological point of view. It is in the sinking air of the Pacific anticyclone. The austausch or exchange layer is shallow and often limited by a strong inversion. The mountain stations are above this layer.

In reply to Mrs. Sagalyn, I believe it can be said that there are two exchange layers, one in the valleys and one above the mountains; the latter is created mainly by daytime convection developed by the mountains.

Mrs. Sagalyn--When we made the measurements in Southern California in the early part of the summer with Dr. Holzer, we made about 17 flights between 500 and 15,000 ft above the top of Mount Palomar, which has an elevation of approximately 6000 ft above sea level. We also flew over White Mountain which has an elevation of 14,000 ft. The height of the exchange layer was found to vary between 500 and 5000 ft over the top of Mount Palomar with an average height of 1500 ft. The top of the mountain was not found to be out of the layer during the period of measurement.

Dr. Byers--How did that compare with New England?

Mrs. Sagalyn--We have not made measurements of the exchange layer over Mount Washington. All our measurements have been over flat terrain in New England.

Dr. Holzer--What Professor Byers said is essentially correct, and the effect that Mrs. Sagalyn mentions is primarily a daytime effect. The effects she described were well shown in the resistance

curves this morning. I believe that in the wintertime and at night that the exchange layer is below the tops of the mountains or is very shallow over mountain tops.

Dr. Byers--I think there are two exchange layers. One, in the valley, does not penetrate to the mountains. The mountains are able to develop an exchange layer of their own especially during the daytime.

Dr. Weickmann--Is this exchange layer always connected with the top of the haze layer or with the cumulus clouds or with any other special condition or is this just a layer you find in your ion measurements?

Dr. Byers--Mrs. Sagalyn said yesterday that nearly always an inversion layer is visible from flights.

Mrs. Sagalyn--There is not a temperature inversion all the time, but there is always a change to a more stable temperature lapse rate at the top of the layer. The top of the layer is most clearly marked by a rapid change in the electrical properies with altitude.

Dr. Chalmers--Have we finished on that?

Dr. Israël, will you comment on Dr. Hogg's paper?

Dr. Israël--If I understood Dr. Hogg correctly his constant, a, is related to the potential of the equalizing layer. We attempted to find a relation between the potential gradient at the ground and the sunspot index used by Dr. Bauer some decades ago. Does the value of a correlate with sunspot numbers?

Dr. Hogg--There was no consistent correlation found between sunspot numbers and the values of a.

Dr. Chalmers--Dr. Tamura has a comment on Dr. Kasemir's paper.

Dr. Tamura--My question is a theoretical one. According to Maxwell's equations if the electric field varies with time and conductivity of the air is not uniform, then the magnetic field varies with time. I think this magnetic field variation will be large. Can we leave this magnetic field out of consideration?

Dr. Kasemir--I do not understand that exactly, but the current is so small I do not believe that the magnetic field would be important.

Dr. Chalmers--Dr. Schilling, you had some remark on Dr. Kasemir's paper?

Dr. Schilling--I had a very straight forward question. Did you have the opportunity to compare the measured air-earth current density with computed values?

Dr. Kasemir--We have not had the opportunity. We have measured the potential gradient and the air-earth current. The agreement is so good that it appears as if one measurement controls the other measurement. Therefore, I believe the measurement of air-earth current is correct.

Dr. Schilling--I concede at the moment this inference--but this is not the case in our complete measurements, including conductivity.

Dr. Chalmers--Any other comment on Dr. Kasemir's paper?

Dr. Swann--If I understand this method correctly, the principle involved in this discussion can be illustrated simply, as follows. We observe that the magnetic field of the Earth varies in one way and the electric field of the Earth varies in another. We say that a changing electric field produces a magnetic field, and a changing magnetic field produces an electric field; and if we work matters out, we find a relation between the time variations of the electric and magnetic field.

We say, 'This is fine.' Perhaps we have a theory of one change in terms of the other. Then we start to work out the order of magnitude and find that the change of the electric field due to the change of the Earth's magnetic field is enormously too small and the change of the magnetic field due to changes of the electric field is enormously too small.

Why were we deceived in this matter? The fact is that because if two variables are related in a simple fashion, qualitatively, they are not necessarily related by direct cause and effect. In the present case, the relation of the electric and magnetic fields goes back in large part to their common relation to the atmospheric tides.

Dr. Chalmers--We now have three questions related to one another, also relating to Mr. Ruttenberg's measurements at sea.

Dr. Gish--The thing that impressed me about your records was the rapid variation in potential gradient and, to a lesser extent, in conductivity. In the first place, I presume that the time constant of your potential gradient collector was rather small.

Mr. Ruttenberg--Yes.

Dr. Gish--One could account for the contrast between what we found on the Carnegie and your records, by the fact that we had a time constant of a minute. What was the time constant for your conductivity instrument?

Mr. Ruttenberg--The time constant of the conductivity instruments is small, the order of a few milliseconds, but the time constant of the recorder pen is of the order of a few seconds. We believe the noise exhibited in the records is real and constitutes small variations in the parameters.

Dr. Gish--I am very much surprised at the type of record for conductivity. I do not know how you could account for it, especially at sea. During thunderstorms on land, occasionally we could get things of that sort, but at sea we never saw anything like that.

Dr. Holzer--During the night on mountains, we have obtained very much smoother records than over the seas. I do not think it is an instrumental question. I think it is a true noise because under favorable conditions, the same devices used at sea will give smooth records.

Dr. Schaefer--This is the same type of effect we obtain with our radioactive probe. At times it will have this same kind of noise, other times it will be absolutely smooth with similar amounts of wind. I agree with you, it is not instrumental. It is a real effect related to a phenomenon in the atmosphere which we need to know much more about.

Dr. Byers--I just wanted to ask if this was in any way related to the speed of the ship? Was it due to the effect of the bow of the ship in creating something that was coming up from the sea? It was a pretty small boat doing 11 knots.

Mr Ruttenberg--The picture I showed of the one quiet day is about as glassy a sea you will ever find in the Pacific. I believe on that day we had a minimum of contamination coming over the rail. With the minimum of spray, we got just exactly the same kind of noise we got on days with winds of 10- 15 knots, with some whitecaps, and considerable swell.

Dr. Chapman--In further confirmation, I can say that with my radioactive p. it and with generating voltmeters, which are different kinds of instruments, we too find this noise on quiet days. It is not instrumental. There are also times when the records are perfectly smooth.

Dr. Parkinson--I have noticed on conductivity traces made at Watheroo, using a quadrant electrometer, that during calm weather quite large 'noise' of period one to several minutes. They appear to be due to inhomogeniety in the air that can persist in calm weather.

Dr. Gish--Did you not mean it the other way, the windy days the curve is more disturbed than on quiet days?

Dr. Parkinson--I very often find large fluctuations on calm nights.

Dr. Holzer--We have made a very large number of measurements now on mountain tops in California and on the Hawaiian Islands, and we have found a very systematic variation of noise on mountain tops, especially in potential gradient records.

Beginning in the morning, the amplitude of the noise increases reaching a maximum at mid-day and diminishing toward night.

Dr. Wormell--I should like to confirm the existence of the effect; if one uses a high-speed method of recording the potential gradient, and if the sensitivity is sufficiently high, noise is present on the record with an appreciable energy down to frequencies of one cycle per second or even several per second.

The amplitude is extremely variable and tends to be greater on a windy day than on a quiet day, but the amplitude of the noise may suddenly increase to a much more disturbed condition, without obvious reason. If one is trying, for example, to record the effect of field-changes due to distant lightning discharges, say 200 km away, the limit for the sensitivity that one can use is just this noise on the record.

Dr. Swann--One must realize that near the surface of the Earth there is a tendency to build up an excess of positive ions (the electorde effect). The turbulence near the surface of the Earth is constantly tending to destroy this space change by mixing. The fluctuations in conductivity and gradient are probably associated with this turbulent process.

Dr. Chalmers--If I may add something myself, we found that the potential gradient variations are very much reduced when inversion conditions which stop this turbulence exist.

Dr. Norinder--I think that in studying this problem one should make measurements of the potential gradient at two stations a few hundred meters apart and compare the records. In this way one can study the movement of changes in the atmosphere.

Dr. Chalmers--That is what we did do.

Dr. Norinder--What distance?

Dr. Chalmers--100 meters.

Dr. Norinder--And did you find that?

Dr. Chalmers--We found that the effects were moving with the wind.

Dr. Schilling--We have performed the experiments which Dr. Norinder asks for. We have established networks with as many as four potential gradient instruments. We obtained results

similar to those of Dr. Chalmers. Some disturbances travel with the wind within the first few meters of the surface. Others are higher as we have found by placing some instruments on the ground and some on the tops of buildings and observing the passage of the same disturbance over successive instruments.

Dr. Chalmers--We found the same disturbance passing over a square-shaped building, with one instrument on one side and one on the other. If it was the ground wind, the building would have disturbed it.

Dr. Gish--We have made various tests at times to determine what factors affect what we call the reduction factor. On one occasion, we put a potential gradient instrument on a tower some 12 or 15 ft high, at the same time gradient measurements were made at the observatory a hundred yards away. The agitation of the potential gradient would start in the morning rather abruptly, and stop rather sharply in the evening at the observatory.

On the tower, however, the effect was not so conspicuous. I have always assumed that what we had was a gentle disturbance of the sand layer which produced enough charge to cause that agitation. I think that the variations of the conductivity were not adequate to account for it.

Dr. Swann--There is one matter on the standardization of potential gradient measurements which I put down many years ago when I was in charge of the earlier work of the Carnegie Institution. I make reference to a plan for obtaining a stable platform (for standardization experiments) at sea. The apparatus is something like a hydrometer. A platform is joined by a rod to the large body floating under the surface. The submerged body is below the region of disturbance and the rod is thin, consequently the platform is not affected by the surface motion of the water.

Also I wish to make a remark about radioactive collectors. It is to be observed that the usual statement to the effect that the 'collector assumes the potential of its surroundings' is misleading. The true operation is as follows. Any rod erected in an electric field acquires a distribution of charge. What the collector does is to reduce the field and so the charge density at the collector to zero. The potential to which the system arises in order to accomplish this is proportional to the 'field' in which the apparatus is erected.

Dr. Chapman--What Dr. Swann has said is enlightening, and correct for a radioactive probe drawing no current whether or not the electrode is served either manually or automatically to a potential which, as Dr. Swann says, reduces the field at the collector to zero. A corona point, radioactive or not, works in quite a different fashion. In this case, depending on the height of the point and the amount of radioactivity, the corona current of the order of 0.003 to 30 microamperes is a measure of the field in which the point has been placed, and perhaps of other things.

Dr. Chalmer -Is there any further discussion on these various papers? I think we will now come to the three separate sections of Dr. Fuchs' papers.

Mr. Smallman--I wished to ask if all whistlers were always of a descending frequency.

Dr. Fuchs--Yes, always decreasing.

Dr. Wormell--'Clicks' observed by Dr. Fuchs are indications of lightning discharges to Earth; 'grinders' are presumably from cloud discharges not, I think, glow discharges. There is strong evidence that 'whistlers' also arise originally from lightning. They are often preceded by 'clicks' [see a recent paper by Storey in Phil. Trans. R. Soc., 1953]. I suggest that correlations of 'whistlers' with other meteorological parameters are primarily correlations of thunderstorm activity with other parameters.

Dr. Fuchs--If the whistlers are in any way connected with lightning discharges, it is naturally possible that if flashes generate clicks (produced in the channel) and whistlers (produced by the tail) at the same time, both are heard if both have nearly the same amplitude. This will be the case if the distance of the thunderstorm is not too great.

Due to attenuation of signals from distant flashes and due to the short duration of the click, it may not be heard, whereas the whistle, due to its longer duration, may have an integrated effect on the ear and may be heard, even without an amplifier in a long wire.

I remember that I observed some whistlers preceded by a click at Sonnblick Observatory. But due to the small number of these cases, I was not led to think about possible connections. I believe now that these cases belong to flashes of medium distance. Therefore, I agree with Dr. Wormell.

Dr. Norinder--In studying the problem of whistlers and atmospherics, I recommend setting up of two or three stations at convenient distances of separation to make simultaneous records of the electromagnetic variations, as for example the electric field components produced by the lightning strokes. Such simultaneous records have been obtained at two stations in Sweden separated by a distance of 570 km. Simultaneous records have been taken from lightning strokes occurring either in Sweden or in other parts of Europe. Theoretical calculations must be considered only as a guide. The real variations of the atmospherics themselves are too complicated to be fully explained by theory at present [see Norinder, The waveform of the electric field in atmospherics recorded by two distant stations, Arkiv för Geofysik, Kungl. Vetenskaprakademien, Stockholm, 1954].

Mr. Reynolds--I wish to mention that Dr. Newman has proposed a sferics network which will include stations at our Institute in Socorro, his Institute in Minneapolis, and at the University of Florida. We hope to make the measurements suggested.

There is another suggestion about whistlers. Dr. Newman has suggested to me that they may be due to variations in the velocity of the leader stroke. There are marked variations in the discharges from negative charge centers to ground, possibly enough to account for the whistler.

Dr. Holzer--I was very much interested in Dr. Fuchs history of the work on whistlers in Austria. I intended in the morning paper to report very briefly on some correlations which we have obtained within the past few months. Mr. Oliver Deal who is working in my laboratory has been measuring natural electromagnetic signals in the frequency range between approximately 50 and 100 cycles per second.

During March, Mr. Deal measured the mean intensity of electromagnetic fluctuations and found that the mean electric vector is of the order of 10^{-4} volts/meter. He also found that there was a mean diurnal variation over a period of 16 days which rather closely paralleled the potential gradient measurements at sea. The principal maxima in the diurnal curves occurred at 16h and 20h GCT which was very close to the time of the principal maxima of the potential gradient at sea.

We are very well aware of the danger of drawing generalizations from 16 days of measurement, and I am not presenting this as final proof of a correlation between these observations and the gradient However, Mr. Deal, in collaboration with Dr. Liebermann of the Scripps Institution of Oceanography has shown these electromagnetic variations are, in large part, due to sferics, and preliminary calculation has indicated that these low frequency signals could arrive from Africa and South America with integrated intensities proportional to total thunderstorm activity if the attenuation were sufficiently low. The possibility that such measurements might ultimately provide an index of world thunderstorm activity makes further study in this direction important.

I would be particularly interested in comments by Mr. Maple who is here from the Naval Ordnance Laboratory and who has been working in this field for some time. I believe he presented

some information to the American Geophysical Union in the early part of this month, and I would like to know whether he has any further evidence on this problem.

Mr. Maple--Our measurements agree with those reported by Dr. Holzer in that the magnetic fluctuations at these frequencies around 100 cps are connected with sferics. We, however, obtain a maximum at local midnight at these frequencies, although this night maximum is much less pronounced at 100 cps than at the higher frequencies. Simultaneous measurements in Florida and Alaska indicate that the attenuation with distance is considerably less at 100 cps than at higher frequencies. What was the local time of your maxima?

Dr. Holzer--The maxima at 16h and 20h GCT correspond to 08h and 12h local time, respectively.

Dr. Wormell--The 'slow tail' of an atmospheric wave form with predominant frequencies of the order of a few hundred cycles per second is propagated with very low attenuation and at distances of several thousand kilometers frequently exceeds in amplitude the higher frequency portion in the earlier part of the wave form.

Dr. Chalmers--Any other points on the first two sections of Dr. Fuchs' papers on whistlers and grinders? Now we will come to the second section of Dr. Fuchs' paper, measurements in storms. Dr. Chapman, you have something on that?

Dr. Chapman--Electrical effects generally are observed at the ground by both generating voltmeters and corona points when substantial precipitation processes are occurring in the cloud, whether or not rain is observed at the station. On occasions, however, very light precipitation or drizzle can occur at the station without electrical effects.

Dr. Chalmers--We now come to Dr. Norinder's paper.

Dr. Weickmann--I would like to make one comment. I am a little afraid you are not measuring only the charge of friction of snow against snow, but other charges.

Dr. Norinder--We have done some experiments in which we coated the tube with ice. When snow was blown against the snow block, we obtained considerable charge on the snow block.

Mr. Cotton--We have observed the same thing.

Dr. Wormell--It is really the same question, but I have also wondered how conclusively we know that blowing snow produces charges by the collision of the snow flakes with one another. Does Dr. Norinder consider that this coating the tube with ice shows conclusively that snow in the free air can be charged by collision and that the solid ground is irrelevant.

Dr. Norinder--In 1920, I performed an experiment in which snow from two tubes was blown together. A tremendous charge was generated in this way, but I was afraid to publish the data because I was not sure about the intricate affair.

Dr. Chalmers--In my original announcement about today's program, I mentioned that there would be a short discussion of the MKS system. With your permission, I would like to introduce the subject.

The first point I would like to make is the MKS system has been officially recognized as the right system to use, and those who don't use it are going against the officially recognized system. Apart from that, atmospheric electricity is one branch of physics in which the MKS system is particularly appropriate, as we have both electrostatic and current electricity formulas. As an example, the apparent current due to induced charge change may be calculated by both the MKS

System and the older methods for a field change of 200 V/m in one second. The MKS System requires just the memory of ϵ_0 while four separate acts of memory are required for the older system. I think this is a very good argument for the MKS systems. What are your opinions?

Dr. Holzer--We have been using MKS units for about a year. I think the strong arguments in any choice of units hinge on convenience and international agreement. In view of the international agreement, I think we should follow the practice of using the MKS system. The MKS system is certainly more convenient than the mixed systems used by some workers in the field.

Dr. Norinder--In Sweden we adopted the MKS system in the technical universities two years ago, and it has worked out very well. Now it is used in universities and also in technical schools. All text books now published employ the MKS system.

Dr. Chalmers--Any objections?

Dr. Parkinson--I think everyone uses volts per meter rather than electrostatic units per meter, but that is the only place I can see in atmospheric electricity where it is necessary to depart from the electrostatic system. The reason is that this is the only place where atmospheric electrical measurements touch the field of magnetism at all. Using the electrostatic system, of course, has a disadvantage, in speaking to other physicists working with the MKS system. Also there may be some confusion in units which is a very strong argument, but I think this is one field where the electrostatic system is ideal to use.

Dr. Chapman--The choice of system of units is largely a matter of convenience. Everyone has his own opinion. I have used the MKS system for about ten years, and I have found it the simplest to use. One point is worth noting, a matter of the ease of converting equations written in the MKS system to equations in the Gaussian or electrostatic systems. I hope this group will agree that the MKS system has advantages.

Dr. Fuchs--I should like to call your attention to the fact that in 1950 the MKS system became the legal system in Austria. I served as a member of the committee to study the law. For four years the advantages and disadvantages of the system were discussed. No significant disadvantages could be found and the law was passed.

Dr. Chalmers--We now come to Dr. Nolan's papers.

Dr. Pluvinage--Does Dr. Nolan think that the assumption of condensation nuclei being made of dielectric substance is reasonable? If so, this would introduce a new parameter, the dielectric constant, in Bricard's theory. Then the agreement with the experiment could be restored. I add that the relation of Boltzmann's law with Bricard's theory ought to be made clear.

Dr. Nolan--It is possible that Bricard's numbers would be improved by bringing in the dielectric constant of the water rather than treating water as a conductor.

Mrs. Sagalyn--There is a question about the calibration of the photoelectric nucleus counter. What is the accuracy?

Dr. Nolan--I consider it very low, 15 to 25 pct, but the measurement of the concentration ratio is much more accurate. The determinations of Z/N_0 and of D (the diffusion coefficient) depend on the ratio and are reliable. The determination of the coagulation coefficient, however, depends on the absolute calibration.

The absolute accuracy of the photo-electric counter is not as high as the absolute calibration depends on the Aitken counter. For relative measurements such as Z/N_0 and Z_V/Z the accuracy is much higher.

The multiple charges on nuclei are inferred from the relation between Z/N_0 and the radius. Direct measurements indicate that the ordinary atmospheric ions carry between one and two electronic charges per ion.

Dr. Schilling--Was it possible from your experiments to determine whether or not atmospheric nuclei were multiply charged? To be more specific, could you infer under what conditions atmospheric nuclei possess a double charge?

Dr. Nolan--The experimental Z/N_0, radius curve departs from the theoretical single-charge Whipple-Harper relation at about 4×10^{-6} cm radius. This departure is interpreted as evidence of double charging. Under equilibrium conditions, multiple charging depends on the radius of the nucleus.

Radii for 2-, 3-, 4-, 5-fold charging using the Boltzmann distribution law are given in the paper.

Mr. Barklie--Possibly out of balance positive or negative space charge might be associated with multiple changing.

Dr. Hogg--Determination of the average charge on large ions by parallel observations with a nucleus counter for charged nuclei and with an ion counter for large ions showed that on the average the large ions carried unit charge except for quite low concentrations of ions when multiple charges were observed.

Mr. Barklie--I have a simple and direct question which may help Dr. Nolan. Does Dr. Nolan think it is worth while to use the Nolan type nucleus counter at a series of different over-pressures; and if so did you calibrate in this way?

Dr. Nolan--We did calibrate at four over-pressures.

THEORIES OF THUNDERSTORM ELECTRIFICATION--SOME GENERAL CONSIDERATIONS

T. W. Wormell

Cavendish Laboratory
University of Cambridge, Cambridge, England

Abstract--The paper will consider certain conditions which a successful theory of charge generation in thunderclouds must satisfy and will then attempt briefly to assess the adequacy of various processes which have been suggested. The importance of electrical 'influence' mechanisms will be emphasized, not merely in terms of the original Wilson theory, but more particularly with regard to their effects in modifying or limiting the results of other mechanisms.

Introduction--Progress towards an acceptable theory of thunderstorm electrification has been disappointingly slow over the past twenty years or more. There was a period when the choice seemed to lie between two possibilities, namely, first, a charging of the larger precipitation particles by some form of 'influence' mechanism which acts in such a manner that the vertical separation, by fall under gravity, of the larger and smaller particles causes an intensification of any pre-existing electric field; the sign of the field thus built up would depend entirely on the sign of the electric field initially present. Theories of this type derive from ELSTER and GEITEL [1913]; the picture was considerably modified and made more acceptable in the form of a selective capture of ions of one sign by the larger particles, by WILSON [1929]. The alternative picture postulated the existence of a vigorous process of separation of charges in the developing thunderstorm which was spontaneous in the sense that it did not depend on the initial existence of a large-scale electric field. Simpson [SIMPSON and SCRASE, 1937] has advocated the view that, at different levels in the cloud, the important processes are the violent rupture of water drops and the friction, or fracture in violent collisions, of ice crystals.

Of recent years various other possibilities have been discussed and, in particular, following the pioneer work of FINDEISEN [1940, 1943], the electrical effects associated with the release of small ice splinters during the growth of ice particles, especially by the process of riming, have been discussed in some detail.

We are still very far however from a position where it has been demonstrated that any known single process can produce, qualitatively and quantitatively, the charge distribution which is known to occur in a cumulo-nimbus cloud. On the other hand there are several processes which we do not know can be completely neglected. It remains a possibility, of course, that several independent mechanisms play a significant role but it seems somewhat unlikely that the electrical effects which appear in so much greater intensity in cumulo-nimbus than in frontal rain are to be ascribed to several independent processes of nearly equal importance.

Conditions to be satisfied--A satisfactory theory of thunderstorm electrification must fit, meteorologically, into the scale in time and space of a cumulo-nimbus cell. The active stage, during which the really violent electrical effects first appear, is comparatively short, of the order say of 30 minutes, but is normally preceded by a longer-lived and comparatively quiescent cumulus stage, and it is perhaps unsafe to assume that no important electrical changes occur during this period.

The typical thundercloud extends far beyond the freezing level and contains much ice in its higher levels, and it is usually considered reasonable to examine mechanisms for which the presence of ice is essential. It is a point of much interest and importance, therefore, to know the nature and intensity of the electrical effects associated with showers from warm clouds, which are known to contain no ice, and in particular whether lightning can ever occur under such circumstances.

Certain investigations by SMITH [1951] suggest that the occurrence of fairly heavy rain without pronounced electrical effects affords a method of identifying occasions of rain from 'non-freezing' clouds, which is an uncommon phenomenon in England.

While the electrical structure of a thundercloud, when examined in detail at close quarters may present an appearance of overwhelming complexity [GUNN, 1950], methods of observation which smooth out the local irregularities have disclosed a systematic and in some ways remarkably simple behavior. Thus, for example, a record of the electric field, and the field-changes due to lightning discharges, taken at say 20 km from the storm, will not infrequently show a series of nearly equal field-changes, at regular intervals of the order of perhaps 10 to 15 sec, the whole record suggesting something of the nature of a relaxation oscillator. The electric moment of the charge distribution destroyed by a typical lightning discharge (that is, 2qh where q is the charge neutralized or removed to Earth by the flash and h is the difference in the mean heights of the two charges neutralized in a cloud discharge or the height of the single charge removed to Earth) is of the order of 100 coulomb km. The initial rate of recovery of the electric moment after a discharge is on the average about 1/7 sec^{-1}; this appears to demand the presence in the electrically active volume of the thunderstorm cell of positive and negative charges of the order of 1000 coulombs, those of one sign (actually the negative sign) being carried on precipitation particles while the opposite charge is carried in the same volume by particles whose velocity of fall under gravity is much smaller [WORMELL, 1953].

Statistical studies of field-change records [WORMELL, 1953] and observations with sounding balloons [SIMPSON and SCRASE, 1937; SIMPSON and ROBINSON, 1941] have established that the main electrical structure of a thundercloud is bipolar and normally of positive polarity, that is, the mean height of the main positive charge exceeds that of the negative charge. The Kew observations also showed that not infrequently there is also a smaller positive charge low down and near the base of an active thundercloud. Simpson and Robinson summed up their observations by stating that a typical structure consisted of an upper charge of +24 coulombs centered at a level where the temperature is about -30°C, a negative charge of -20 coulombs centered at about -8°C and a lower positive charge of +4 coulombs centered near the 0°C level or at rather higher temperatures. Rather similar results have been found by KUETTNER [1950] in observations on the Zugspitze; he claimed that on the average the lower positive charge was centered exactly at 0°C.

Our knowledge is still very incomplete concerning the detailed manner in which the electrical structure varies during the life-cycle of a cumulo-nimbus cell. Again, while it seems to be well established that the main structure of the great majority of clouds is one of positive polarity, can we say with certainty that storms of the reverse polarity never occur? The sequence of phenomena observed at a single observing station does occasionally suggest a cloud of negative polarity but such observations are of course inconclusive.

<u>The problem of the main charges</u>--The small and very localized lower positive charge will not be discussed in any detail; it may well be a secondary phenomenon.

When we turn to the main bipolar structure it is clear that, as far as any theory of a frictional type is concerned, data are lacking for any sort of quantitative check even if it be shown that, qualitatively, charges of the correct sign can be produced. Let us consider for a moment the influence theory. The simple picture, as painted by WILSON [1929], has to face two main difficulties; first, the process appears too slow unless additional sources of ionization appear at some stage in the development of the field, secondly, the selective capture of ions of one sign by precipitation elements ceases when the field becomes so strong that the velocity of ions in the field exceeds the rate of fall of the precipitation particles. In the case of small ions the critical field is thus of the order of a few hundred volts per centimeter. For the development, by this mechanism, of fields sufficiently intense for the occurrence of lightning a plentiful supply of large ions, but very few small ions, would seem to be a necessity in the later stages, while earlier, in order that the selective charging may proceed at a reasonable rate, small ions would seem to be a necessity. It is not easy to see in detail how these conditions can be met. This is not to say, however, that the process can be forgotten

altogether; it will always be at work modifying the charges on the particles, modifying the effects of other possible processes and possibly producing secondary charge distributions as a result of the field due to the primary process, whatever that may be.

Consider, for a moment, the effects of the process. The equations have recently been summarized by WORMELL [1953]. We may, however, state them in a slightly different way, in language familiar in cloud physics by giving the collection efficiencies of a precipitation particle for ions under different conditions. It is necessary first to specify precisely what we mean by this term; in an electrical field the ions may be moving with velocities comparable with that of the falling precipitation particle. I propose to define two quantities for a spherical precipitation particle of radius a in a large scale vertical electric field X. The 'collection efficiency' E for ions will be defined as the ratio of the number of ions captured by the particle per second to the number which cross, in one second, a horizontal surface of area πa^2 which is moving downwards with a velocity V equal to the fall velocity of the particle. From another point of view we should be more interested in what may be called the 'electrical efficiency' E' defined as the ratio of the number of ions caught per second by the particle to the number crossing, per second, a stationary horizontal area πa^2 which is remote from the particle; alternatively, the electrical efficiency is simply the ratio of the rate of increase of the charge on the particle to the vertical current through an area πa^2. Values of these two quantities, which may of course be deduced at once from the equations of WHIPPLE and CHALMERS [1944], are given for a few particular cases in Table 1.

Table 1--Collection efficiencies E and electrical efficiencies E' for capture of ions by spherical conducting particles of radius a and velocity of fall V; Q is the charge on the particle, w ionic mobility, X vertical electric field (assumed directed downwards); E and E' are defined in the text

Case	Condition	Ion charge	E	E'
I	Q positive	Negative	$\frac{4wQ}{a^2V}$	∞
	X zero	Positive	0	0
II	Q zero	Negative	$\frac{3}{1 + V/wX}$	3
		Positive: $V>wX$	0	0
		Positive: $V<wX$	$\frac{3}{1 - V/wX}$	3
III	$-3Xa^2<Q<+3Xa^2$	Negative	$\frac{3(1 + Q/3Xa^2)^2}{1 + V/wX}$	$3(1 + Q/3Xa^2)^2$
		Positive: $V>wX$, $Q>0$	0	0
		$Q<0$	$\frac{4\|Q\|/Xa^2}{V/wX - 1}$	$4\|Q\|/Xa^2$
		$V<wX$	$\frac{3(1 - Q/3Xa^2)^2}{1 - V/wX}$	$3(1 - Q/3Xa^2)^2$

The equations to which the formulas of Table 1 are equivalent were deduced in the first place for the case of viscous flow around the particle the motion of the ion relative to the air being at each point simply the product of the ionic mobility and the local field which itself is the vector resultant of the large-scale vertical field X and the field due to the charge and the polarization of the particle. They neglect the small effect due to the influence of the ionic charge on the polarization

of the particle when the ion is very close to the particle's surface. The equations are probably reasonable approximations when the particle is as large as a raindrop or graupel pellet.

The essential feature of these results is that, if the large-scale field is directed downwards, and if the fall velocity of the particle $V > wX$, where w = ionic mobility and X = vertical field, an uncharged particle captures only negative ions and its final equilibrium charge is negative. This equilibrium charge is independent of the number of positive ions in the space surrounding the particle which may be much more numerous than the negative ions. On the other hand, if $V < wX$, the sign of the equilibrium charge depends on the relative numbers of positive and negative ions. If any process is giving negative charge to the particles, and there exists a downward vertical field X (which may have been largely produced by the fall of the negative particles), then, within certain limits, the negative charge on the particles is stable; it is not neutralized by the corresponding positive charge which may be present in the form of ions in the space surrounding the particles.

In a cumulo-nimbus cloud the role of the 'ions' may be played by charged small cloud particles or ice-splinters. There are now two complications; these 'ions' possess inertia and secondly they are of finite size and are themselves polarized in the electric field and the force between them and the larger particles thereby modified. Both these effects alter the collection efficiencies and their computation becomes very complicated. PAUTHENIER and COCHET [1953] have published calculations for some particular cases and have shown, in particular, that the collection efficiency of a charged water drop for cloud particles, even when the latter are uncharged, is greatly enhanced by the electrical forces for certain ranges of size. Such effects may be important when the considering the growth of precipitation particles as well as when the main interest lies with electrical effects.

In order to clarify the point which it is desired to make let us consider a particular process, the growth of a pellet of ice by riming, that is, by the collision with and capture of supercooled water droplets. Various writers, for example KUETTNER [1950], have urged the importance of this process in the physics and electrification of thunderstorms; MASON [1953] has attempted to develop a quantitative picture. There is an immediate and initial difficulty in that the results of various laboratory investigations of this process are inconclusive and contradictory. It is clear that it is very difficult to avoid spurious effects and the results may be very sensitive to small changes in physical conditions and to traces of impurity. Let us assume in the first place that riming in itself gives no charge to the growing ice pellet. If, however, there exists a vertical electric field (which for definiteness will be assumed to be directed downwards) the situation is profoundly changed; the ice pellet is polarized, its lower part carrying a positive polarization charge. When supercooled water droplets strike the lower surface of the ice particle, and freeze on it, some of the water may escape, in some conditions as liquid water, in other conditions as small ice splinters. If this escape occurs at the lower surface of the ice pellet, then by simple electrostatics the escaping fragments will be positively charged and the ice pellet will be left with a net negative charge. Subsequent separation under gravity of growing ice particles and 'fragments' will enhance the vertical field with which we started. This is, of course, simply a slightly modified version of the ELSTER and GEITEL [1913] theory. It must also be pointed out that if under certain conditions the ice particle acquires a surface skin of water and sheds water, as it falls, mainly from its upper surface, the charging is in the reverse direction and the final effect is to destroy, in this region of the cloud the vertical field with which we started.

Let us now suppose that riming in itself, (that is, in the absence of an external field) does give a charge to the growing particle. If an external field is present, then the spontaneous charging effect will be simply superposed on the electrostatic effects which have been discussed. These may profoundly modify and even conceivable reverse the sign of the charging observed in the absence of a field. Both FINDEISEN [1940] and LUEDER [1951ab] claimed to have observed the controlling effect of an electric field during riming.

A further point must be considered. If graupel pellets are growing and becoming negatively charged, then an equal positive charge must be appearing in the air around them, this charge being

carried either on cloud particles, on ice splinters or remaining as free positive ions. In the presence of a downward-directed field any positive ions would be rapidly attached to cloud particles if such are present with fall velocities less than the velocity with which the ions are being driven downward by the field. If no particles are present with such small velocities of fall the ions will remain free. Fresh graupel particles which fall into this region are thus falling through a cloud many of the particles of which are positively charged. In the absence of an external field any negative charge on the larger particles would to a large degree be rapidly lost by the capture of positively charged cloud particles. In the presence of a vertical field, however, the Wilson selective capture process prevents this and permits the graupel pellets to acquire and to retain a definite negative charge.

Similar considerations will apply in discussing any other charging process in the thundercloud. In attempting to estimate from the results of laboratory experiments the large-scale effects to be anticipated in a cloud, it is essential to take into consideration the effects of the polarization charges on the particles and the effects of the field in promoting selective capture of ions of one sign. Neglect of these will lead to results which are almost meaningless. The actual carrying through in detail of such a calculation is a matter of great complexity and demands numerous assumptions or an extremely detailed knowledge of the number and nature of the various particles and ions present in the cloud.

References

ELSTER, J., and H. GEITEL, Zur Influenztheorie der Niederschlags-Elektrizität, Phys. Zs., v. 14, pp. 1287-1292, 1913.

FINDEISEN, W., Über die Entstehung der Gewitterelektrizität, Met. Zs., v. 57, pp. 201-215, 1940.

FINDEISEN, W., and E., Untersuchungen über die Eissplitterbildung an Reifschichten, Met. Zs., v. 60, pp. 145-154, 194?.

GUNN, ROSS, The free elect[illegible]l charge on precipitation inside an active thunderstorm, J. Geophys. Res., v. 55, pp. 171-178, 1950.

KUETTNER, J., The electrical and meteorological conditions inside thunderstorms, J. Met., v. 7, pp. 322-332, 1950.

LUEDER, H., Ein neuer elektrische Effekt bei der Eisbildung durch Vergraupelung in natürlichen unterkühlten Nebeln, Zs. f. angew. Phys., v. 3, pp. 247-253, 1951a.

LUEDER, H., Vergraupelungselektrisierung als eine Ursache der Gewitterelektrizität, Zs. f. angew. Phys., v. 3, pp. 288-295, 1951.

MASON, B. J., On the generation of charge associated with graupel formation in thunderstorms, Q. J. R. Met. Soc., v. 79, pp. 501-509, 1953.

PAUTHENIER, M., and R. COCHET, Évolution d'une goutelette d'eau chargée dans un nuage à temperature positive, Rev. gén. de l'Electr., v. 62, pp. 255-262, 1953.

SIMPSON, G. C., and F. G. SCRASE, The distribution of electricity in thunderclouds, Proc. R. Soc. A, v. 161, pp. 309-352, 1937.

SIMPSON, G. C., and G. D. ROBINSON, The distribution of electricity in thunderclouds, II, Proc. R. Soc. A, v. 177, pp. 281-329, 1941.

SMITH, L. G., Contribution to discussion, Q. J. R. Met. Soc., v. 77, p. 683, 1951.

WHIPPLE, F. J. W., and J. A. CHALMERS, On Wilson's theory of the collection of charge by falling drops, Q. J. R. Met. Soc., v. 70, pp. 103-119, 1944.

WILSON, C. T. R., Some thundercloud problems, J. Franklin Inst., v. 208, pp. 1-12, 1929.

WORMELL, T. W., Atmospheric electricity; some recent trends and problems, Q. J. R. Met. Soc., v. 79, pp. 3-38, 1953.

THUNDERSTORM CHARGE STRUCTURE AND SUGGESTED ELECTRIFICATION MECHANISMS

S. E. Reynolds

Research and Development Division
New Mexico Institute of Mining and Technology
Campus Station, Socorro, New Mexico

Abstract--The Workman-Holzer technique for determining the sign, magnitude, and location of charge centers in thunderstorms has been improved and applied to storms occurring in New Mexico during the summer of 1952. The technique and the results obtained are described. The study revealed that the temperature of the environment of the negative charge centers may vary from about 0°C to about -33°C and that the corresponding positive charge center is usually found about 2000 ft above the negative center. The probable charge separation mechanisms are discussed in the light of the charge configuration and the physical environment deduced from this study. Laboratory experiments which demonstrate charge separation mechanisms which can be effective in this environment are discussed.

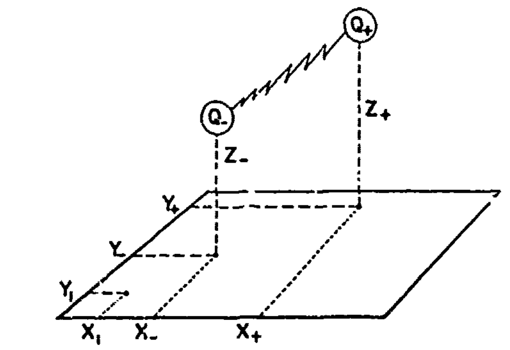
Introduction--The objective of research being done at the New Mexico Institute of Mining and Technology under U. S. Army Signal Corps sponsorship is to describe the physical processes leading to thunderstorm electrification. Knowledge of the environment in which thunderstorm charge centers occur is of crucial importance in studying the validity of any postulated charge-separation mechanism.

Technique--WORKMAN, HOLZER, and PELSOR [1942] developed a technique for locating the charge centers in active thunderstorms. The technique consists essentially of measuring, at a number of positions on the ground, the potential-gradient change accompanying lightning discharges. The theory of this method can best be explained by reference to Figure 1. E is the gradient change at the point x_1, y_1 when the dipole Q+, Q- is discharged by a lightning stroke. If we assume the surface of the Earth to be an infinite conducting plane, it is clear that in the case of the discharge of a dipole we have seven unknowns; the space coordinates of the negative center (x, y, and z with minus subscripts), the space coordinates of the positive center (x, y, and z with plus subscripts), and the magnitude of the charge Q. The magnitudes of the positive and negative charges are equal in the case of a dipole. Thus, if the gradient change can be measured at seven points on a plane, seven independent equations involving the seven unknowns can be written in the form shown. It can be shown similarly that only four measurements are required in the case of a single center discharging to ground.

Using the above theory, Workman, Holzer, and Pelsor conducted a study with a network of eight instruments at an altitude of 5300 ft near Albuquerque, New Mexico. The results of the study were published, but unfortunately the report received only limited circulation because of military classification.

The 1942 study was repeated in the summer of 1952 with the principal advantages of an improved potential-gradient recorder designed by Dr. Workman and at a higher elevation (7000 ft) for the instrument network.

The basic elements of the potential-gradient recorder are an exposed antenna plate, a shielding mechanism, and a recording vacuum-tube voltmeter. The plate current of the electrometer is indicated by the galvanometer and is recorded on 16-mm film which travels approximately one-half



THE NORMAL POTENTIAL GRADIENT CHANGE AT X_1, Y_1 IS,

$$E = \frac{2Q_-Z_-}{\left[(X_- - X_1)^2 + (Y_- - Y_1)^2 + Z_-^2\right]^{3/2}} - \frac{2Q_+Z_+}{\left[(X_+ - X_1)^2 + (Y_+ - Y_1)^2 + Z_+^2\right]^{3/2}}$$

Fig. 1--Sketch showing significance of terms used

Since it is impractical to attempt to solve analytically seven nonlinear, simultaneous equations, the analysis of the data obtained presented a problem of considerable magnitude. Workman, Holzer, and Pelsor used a mechanical analogue to analyze data from their network. The data from the more recent study were analyzed by a trial-and-error technique based on tabulated calculations.

Results--The instrument network was operated during 18 storms on 16 days, but a large number of data was obtained from only two of these storms. It was possible to locate the centers involved in a total of 40 lightning stroke elements.

The results of the study are summarized by Figure 3. The mean height for negative centers involved in intracloud discharges is 24,000 ft msl. The temperature at this height is about -16°C. The negative

inch per second over a 0.001-inch slit. The plate current is proportional to the electrostatic charge induced on the antenna. The time resolution of the instrument (about 0.01 sec) is limited, of course, by the natural period of the galvanometer, the film speed, and the slit width. Figure 2 shows the instrument schematically.

Eleven of the instruments were distributed over an area of about 30 sq mi. All the instruments were connected to the central control station with field telephone wire strung on the ground. This connection, through appropriate relays at the instruments, permitted starting and stopping of all instruments from the central control point. It also provided for automatic simultaneous operation of all antenna shields every ten seconds, as well as for occasional simultaneous operation to provide 'intelligence' signals required in coordination of the records. The instruments were calibrated against a generating-type potential gradient recorder.

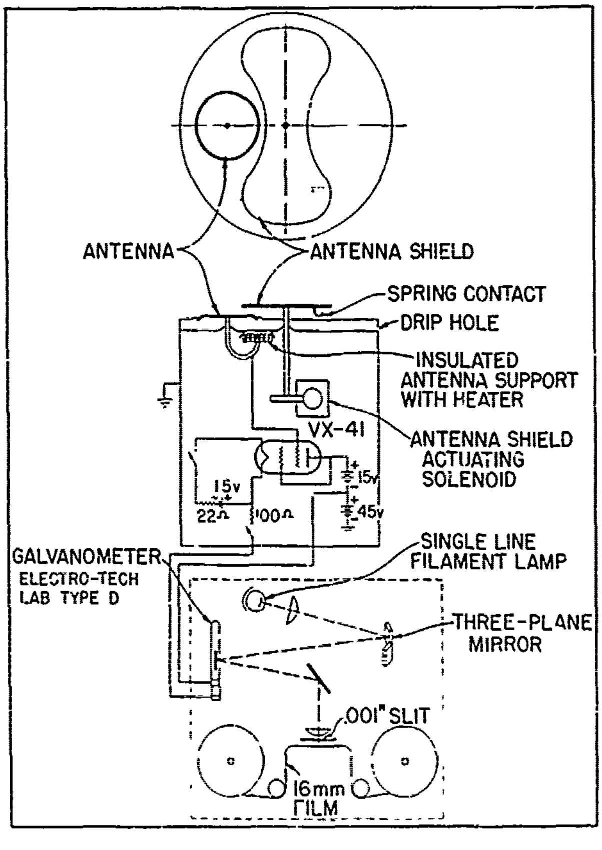


Fig. 2--Schematic diagram of the instrument

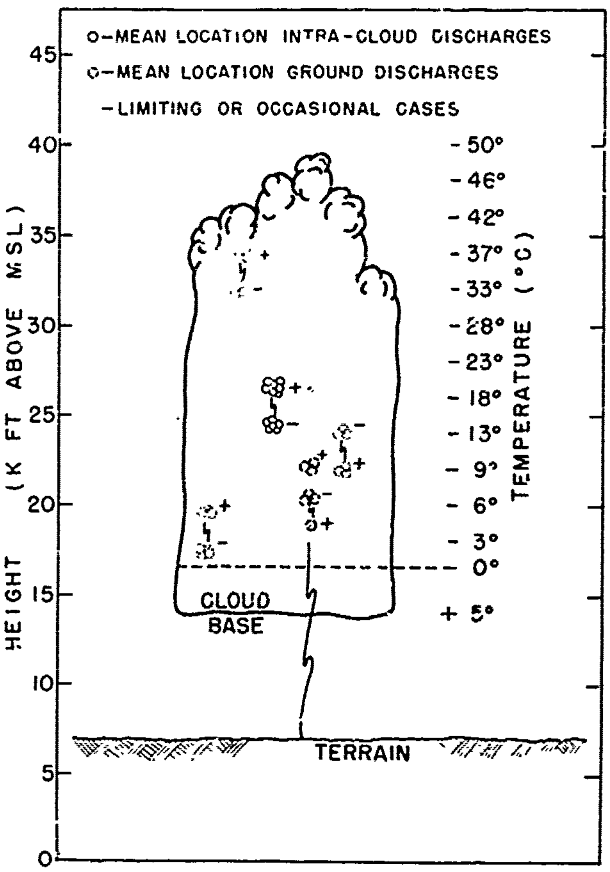


Fig. 3--Results of study

centers may occur at temperatures as cold as -33°C or as warm as -1°C. The corresponding positive charge centers are always closely associated, being on the average about 2000 ft above (or 4°C colder than) the negative center. The horizontal separation (not indicated in Fig. 3) between centers was usually about one-half as great as the vertical separation. While Workman, Holzer, and Pelson found generally greater horizontal separations, the vertical separation and the temperature environment found for the charge centers in this more recent study are in excellent agreement with their findings.

The occurrence of a lower positive charge center, near the 0°C isotherm and in the region of heaviest precipitation, was indicated by the role of these centers in the initiation of discharges to ground, and by the existence of high positive fields at the surface near such regions. The earlier study gave no evidence for the existence of such centers. This difference in the results of the two studies may be attributable to the fact that the instrument network was 1700 ft higher in the second study and therefore provided better resolution.

Charge separation mechanisms--Perhaps the most significant feature revealed by the study is the wide range of temperatures at which the charge centers may occur. If a single mechanism is to account for thunderstorm charge separation it must indeed be a versatile one.

A few years ago we discovered an electrical phenomenon that might be the cause of thunderstorm electrification [WORKMAN and REYNOLDS, 1950]. We found that as dilute aqueous solutions are frozen, potential differences of as much as 250 volts arise between the solid and liquid phases. We also found that a large amount of charge (several hundred thousand esu/cc of water frozen) is separated during the freezing process. The sign and magnitude of the potential difference and the amount of charge separated are dependent upon the kind and amount of material in solution in the water.

We examined the precipitation forms taken from an active thunderstorm cell and concluded that if glaze ice were being formed on precipitation particles and liquid water were being shed from the particles in the course of their fall, a charge dipole having its negative center oriented downward would be developed in the cloud above the 0°C isotherm.

We have made more recently a theoretical study of the formation of glaze ice on precipitation particles as a function of elapsed time and cloud temperature, liquid water content and updraft velocity [REYNOLDS, 1953]. This study suggests that the formation of glaze ice cannot be expected to proceed in New Mexico thunderstorms at temperatures much colder than about -10°C. The relationship of the various factors is illustrated by Figure 4. The dotted line shows the representative maximum theoretical liquid-water content for New Mexico thunderclouds. Coordinates to the left of the line are critical for the formation of glaze ice on precipitation particles. An updraft of

1500 ft/min is considered representative for New Mexico clouds. It should be noted that even though the liquid-water content is as great as the theoretical maximum, and the up-draft velocity is as great as 2500 ft/min, glaze ice will not be formed at temperatures lower than -16°C.

It must be concluded, if the results of the theoretical study are accepted, that the potential differences which accompany the freezing of dilute aqueous solutions cannot a account for charge centers which occur frequently at temperatures lower than -20°C. For this reason laboratory experiments designed to determine whether electrical effects might accompany the growth of precipitation particles by processes not involving glaze ice were undertaken.

The device shown in Figure 5 was constructed to study the electrical effects that might be associated with the formation of rime ice. When the riming element is operated in a supercooled cloud at peripheral speeds of 25 ft/sec, or about the maximum speed of fall for raindrops, a rime ice formation such as that shown is formed. The thin rod which dips into the pool of mercury makes electrical contact with the riming element at a point inside the grounded shield. The mercury pool is connected to a recording electrometer.

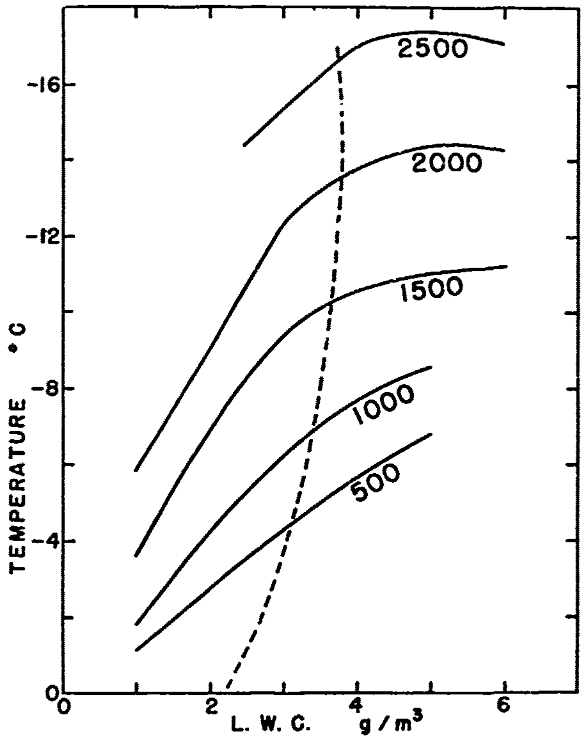


Fig. 4--Relationship of temperature to liquid water content required to produce 'wet' hailstones at given updraft velocity

When the rimer is operated in a cloud composed entirely of supercooled droplets, or a cloud composed entirely of ice crystals, negligible charging effects are observed. However, when the rimer is operated in a cloud consisting of supercooled droplets and ice crystals in coexistence, a large amount of charge (approximately 1 esu/sec) is separated. In general the sign of the charge on the rimer is positive when the crystals are numerous in relation to the droplets, and negative when the reverse situation obtains.

On the basis of some secondary experiments, I suggested at the Santa Barbara meeting of the American Meteorological Society in 1953, that the observed charging effects were attributable to the acquisition of positive charge by the ice crystals as they grew by sublimation. The effects of these secondary experiments were found to be irrelevant or spurious and this interpretation was abandoned.

The riming element is, of course, analogous to a graupel particle growing by the accretion of cloud droplets. Such a particle will have a high fall velocity relative to ice crystals and cloud droplets. From what has been said about the charge configuration in thunderstorms it is obvious that these particles of high fall velocity must acquire negative charge to account for thunderstorm electrification.

The acquisition of negative charge by the riming element apparently is associated with the accretion of relatively large amounts of supercooled liquid water. In these circumstances the temperature of the growing rime ice will be greater than that of the ambient cloud and growing

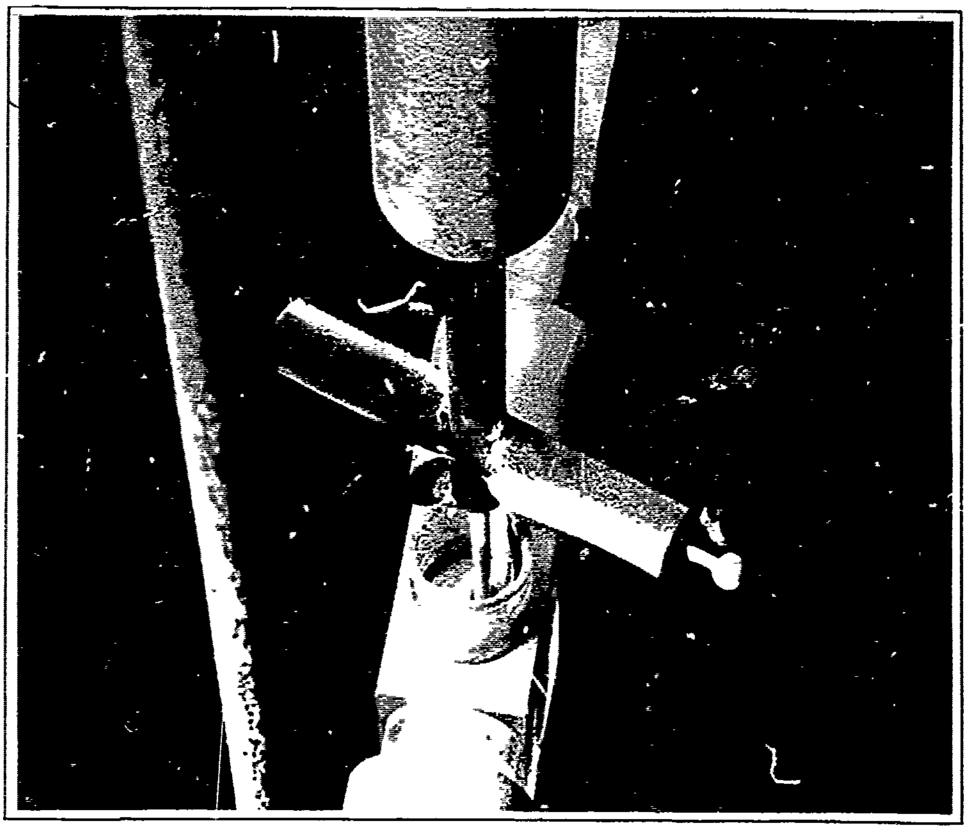


Fig. 5--Instrument for the study of electrical effects associated with the formation of rime

crystals, because of the acquired latent heat of the accreted droplets. To test whether a temperature difference between the rime formation and the cloud might control the sign of the charge acquired, a Westinghouse 250-watt Heat-Ray lamp was arranged so that it could heat the rotating rimer by illuminating it from a distance of about one foot. When the cloud conditions were adjusted for strong positive charging of the riming element, and the rimer was thus heated, strong negative charging promptly resulted.

It was also found that when contaminants which serve as condensation nuclei (for example, sodium chloride smoke) were introduced into the cloud in quantities sufficient to give a concentration of about 10^{-4} molal in the rime collected, the sign of the charge on the rimer was negative, regardless of the relative amounts of water droplets and ice crystals in the cloud. It should be pointed out that the impurities in the cloud result in the contamination of the rime formation, whereas the crystals floating in the cloud remain quite clean. The smoke particles provide condensation nuclei upon which the cloud droplets form. The rime ice grows principally by the accretion of the contaminated droplets, whereas the crystals grow directly from water vapor.

Hypothesizing that charge is acquired by the rime as a result of rubbing contact between the rime and the growing ice crystals in the cloud, Marx Brook and I designed experiments to test whether charge separation resulted from the rubbing of one ice surface upon another. Encouragement for experimentation of this sort was gained from a paper by HENRY [1953], in which it was suggested that a temperature difference between similar surfaces might cause charge separation when they are rubbed together.

Two nickel-plated copper rods were chilled and then dipped into a graduate containing distilled water to form a film of ice about one mm in thickness on the rods. One of the rods was connected to a tube electrometer and the other rod was connected to ground. It was found that if one of the rods was maintained at a temperature 2°C or more, warmer than the other rod, the warm rod always acquired negative charge upon rubbing.

It was also found that if the ice surfaces on both of the rods were formed from a 10^{-4} molal solution of sodium chloride, no charge separation accompanied rubbing contact, regardless of the temperature difference between the formations. However, if one of the ice formations was formed from such a solution and the other was formed from distilled water, the rod having the contaminated ice became negatively charged even when its temperature was as much as 8°C colder than the uncontaminated rod. Cesium fluoride and lithium chloride also were used as contaminants in the same concentrations, and produced exactly similar effects on the frictional charging. It is possible to offer a tentative explanation of t' physical phenomenon which determines the sign of the charge separated during rubbing contact between two ice surfaces. Time does not permit a presentation of all the details. Briefly, however, the sign of the charge separated seems to depend upon the relative mobility of the protons in the two ice formations.

Summary--The experiments involving the rubbing together of two ice formations strongly support the hypothesis that the charge acquired by a growing rime-ice formation results from frictional contact with the ice crystals in the cloud. The effect of temperature difference and the effect of contamination in these experiments is completely consistent with the effects of these variables in the riming experiments.

The mechanism being studied appears to be quite applicable to thunderstorm electrification. In order to account for the observed thunderstorm polarity the precipitation particles having the highest fall velocity must acquire negative charge. Using the equations of LUDLAM [1950], one can show that a four-mm graupel particle, falling through a cloud (fall velocity about 30 ft/sec) having a liquid-water content of only one gr/m^3 and a temperature of -20°C, will achieve a temperature about 2.5°C warmer than the cloud temperature. (The value of one gr/m^3 is low, and this value may be expected to be as high as 3.5 gr/m^3 in New Mexico thunderclouds.) Ice crystals growing by sublimation in such a cloud will be only about 0.5°C warmer than the cloud. Furthermore, the graupel particle will be composed principally of accreted droplets which have been contaminated by their condensation nuclei, and will, therefore, be composed of an ice which is much more contaminated than the crystals which have grown directly from vapor. Thus both of the variables (that is, temperature and contamination differences) which control the sign of frictional charge separation act to cause the particles of high fall velocity to become negatively charged. An important consideration in determining whether the frictional effect can account for thunderstorm electrification is the amount of charge separated per graupel-crystal collision. A preliminary measurement of the charge per collision, when crystals of about 100 micron diameter and a four-mm riming sphere are involved, yielded a value of 5×10^{-4} esu per collision. Using this value, one can compute that the graupel particles would acquire a charge of 5 esu/gram in a cloud containing one gr/m^3 of liquid water and having an ice-crystal concentration of 10^4/m^3. It is recognized that more must be learned about the liquid-water content and ice-crystal concentrations in clouds before valid calculations of this kind can be made. It is rather to be expected that the ice crystals encountered in atmospheric clouds would be much larger than 100 microns and would yield larger amounts of charge per collision.

Acknowledgment--This research work was sponsored by the Signal Corps of the U. S. Army and the New Mexico Institute of Mining and Technology.

References

HENRY, P. S. H., The role of asymmetric rubbing in the generation of static electricity, Brit. J. Appl. Phys., Sup. 2, 1953.

LUDLAM, F. H., The composition of coagulation-elements in cumulonimbus, J. R. Met. Soc., v. 76, p. 52, 1950.

REYNOLDS, S. E., Thunderstorm-precipitation growth and electrical-charge generation, Bul. Amer. Met. Soc., v. 34, no. 3, March, 1953.

WORKMAN, E. J., R. E. HOLZER, and G. T. PELSOR, The electrical structure of thunderstorms, Nat. Adv. Com. Aeronaut. Tech. Note 864, November, 1942.

WORKMAN, E. J., and S. E. REYNOLDS, Electrical-phenomena occurring during the freezing of dilute aqueous solutions and their possible relationship to thunderstorm electricity, Phys. Rev., v. 78, no. 3, May, 1950.

POSSIBLE MECHANISM FOR THE FORMATION OF THUNDERSTORM ELECTRICITY

Bernard Vonnegut

Arthur D. Little, Inc.
Memorial Drive
Cambridge 42, Massachusetts

Abstract--It is proposed that electrification in thunderstorms is the result of strong updrafts and downdrafts that cause a multiplication of the small space charge normally found in the lower atmosphere. Because the air in the lower atmosphere contains a small positive space charge, clouds formed of this air have a small positive electric charge and produce an electric field. Under the influence of this field, negative ions from the upper atmosphere move down toward the cloud. These ions do not neutralize the cloud because they are caught in downdrafts that carry them down to the lower part of the cloud where they accumulate to form a large region of negative space charge. This charge finally becomes large enough to produce a large positive space charge by corona from points on the ground beneath the cloud. Air containing this increased positive space charge is carried by updrafts into the top of the cloud, causing it to become even more positively charged. This increases the rate of growth of the center of negative charge and finally the charges become large enough to produce lightning.

Introduction--This paper presents an hypothesis that is a possible alternative or supplement to the widely accepted theory that lightning is the result of the gravitational separation of charged precipitation elements in a neutral cloud. According to the accepted theory, precipitation particles such as rain, snow, hail, or sleet somehow become charged with one sign, while air or slower-falling particles become charged with the opposite sign. The faster-falling particles then fall away from the slower-falling ones, thereby creating a separation of charge that results in lightning.

Precipitation particles play a minor role in the presently proposed theory of electrification. According to this theory, the charges responsible for lightning are not produced by the separation of oppositely charged precipitation elements but are drawn from the ionosphere by conduction and from the Earth by corona. It is postulated that intense convective activity, such as that occurring in thunderstorms, results in a charge multiplication process that increases the small space charges normally present in the atmosphere until they are large enough to produce lightning. This process is similar to that which takes place in high-voltage electrical induction machines. It appears that the small concentration of positive space charge normally found in the lower atmosphere is usually sufficiently large to begin the build-up of charge. However, the initial charge necessary for a charge multiplication process of this sort might be provided by other sources of space charge such as precipitation, dust storms, blowing snow, ocean spray, or volcanic activity.

Before describing this process of electrification, it is helpful first to review very briefly the observed facts of fair-weather electrical phenomena on which the theory is based. Presumably, because of thunderstorm activity, which is constantly taking place over the surface of the Earth, the ionosphere is maintained at a positive potential with respect to the Earth of the order of half a million volts [GISH and SHERMAN, 1936]. This potential difference causes a positive current to flow continuously through the atmosphere from the ionosphere to the Earth. Because of the high electrical resistivity of the atmosphere at low levels and because of the electrode effect, this current results in a slight excess of positively charged Aitken nuclei in the lower atmosphere [KAHLER, 1927; OBOLENSKY, 1925; BROWN, 1930]. It is postulated that this small positive space charge initiates the electrification process in clouds.

When the atmosphere becomes sufficiently unstable to produce thunderstorms, large volumes of warm, moist air near the ground converge and rise to high altitudes to form clouds. Because this air contains a positive space charge, the clouds that are formed are electrically charged. One of these clouds is shown in Figure 1.

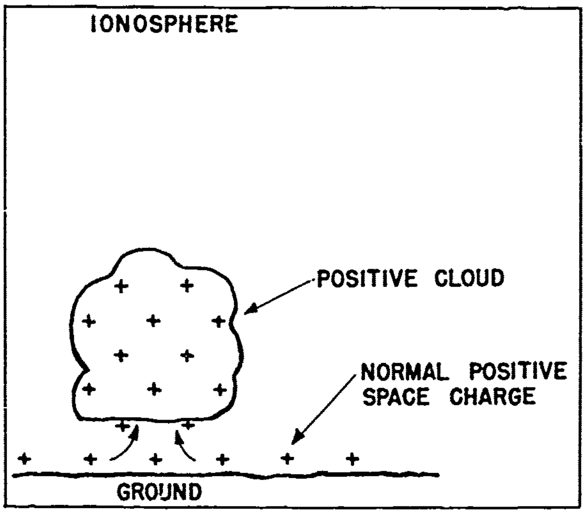


Fig. 1--Formation of cloud containing small positive space charge

Even a very large cloud having the space-charge density usually found in the lower atmosphere would not produce a potential gradient sufficient to produce lightning. However, as the cloud grows and increases in height, another process begins to take place that results in the production of large air masses having a much greater space-charge density. The cloud finally reaches altitudes where the electrical conductivity of the surrounding air is much greater than that at lower levels. The potential gradient at the top of the cloud is considerably greater than the normal positive gradient at these altitudes and in the opposite direction. Under the influence of this field a current of small negative ions flows from the ionosphere to the surface of the charged cloud. Here the small ions attach themselves to cloud particles and Aitken nuclei and thus become large ions of low mobility. This process results in the formation of a negative space charge over the top surface of the cloud, which, were it to accumulate, would soon neutralize the positive field. However, there are rapid downdrafts on the surface of a cumulus cloud that carry the negative charge away from the top of the cloud down to lower levels. The air comprising these downdrafts originally rose from the Earth's surface because it was thermally unstable. Therefore, the air in these downdrafts does not return all the way to the ground, but descends to some intermediate level at which it is in equilibrium. As the result of this process, the negative charge carried down from the top of the cloud by the downdrafts accumulates as a charge center somewhere in the lower part of the cloud, as shown in Figure 2. This charge grows until it finally produces a field large enough to cause points on the surface of the Earth to give corona and produce a current of positive ions. These small ions become attached to Aitken nuclei and cloud droplets in the lower atmosphere and thus become large ions of low mobility. Even in the large electric fields that prevail in thunderstorms, the velocity of these ions relative to the air is small compared to the wind velocity. Therefore these positive ions are prevented by the wind from moving towards the negative charge that induced them, and are carried by updrafts into the top of the cloud, thus causing it to become even more positively charged, as shown in Figure 3. This, in turn, increases the rate at which negative charge is drawn from the ionosphere and carried to the lower part of the cloud. The positive and negative charge centers grow by this process until the resulting potential gradients are sufficiently large to result in lightning.

If the foregoing theory is correct, it must be in accord with the established facts of atmospheric electricity and cloud development and must quantitatively account for the electrical currents that have been measured in thunderstorms. The theory depends on three basic processes: (1) the conduction of charge from the ionosphere to the cloud; (2) the production of corona from the ground; and (3) the transport of these charges by updrafts and downdrafts in such a manner that they are accumulated to give charge centers large enough to produce lightning.

Unfortunately, there are insufficient experimental data concerning such variables as the space charge distribution in the cloud and the air trajectories inside and outside the cloud to permit a rigorous quantitative treatment of the various processes involved in the theory. Nevertheless,

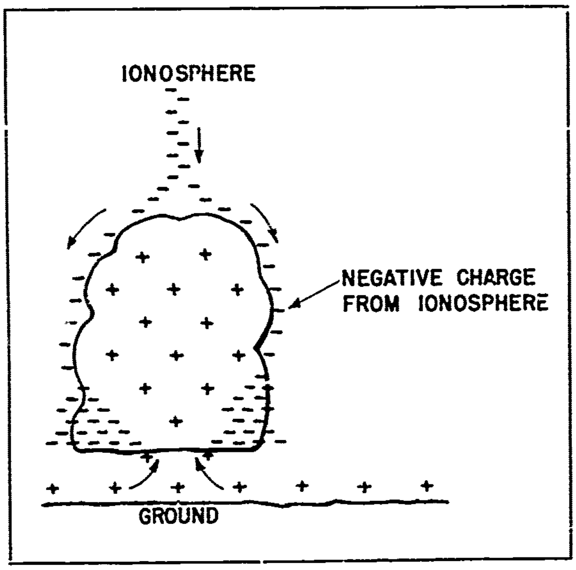


Fig. 2--Development of negative charge center in lower part of cloud

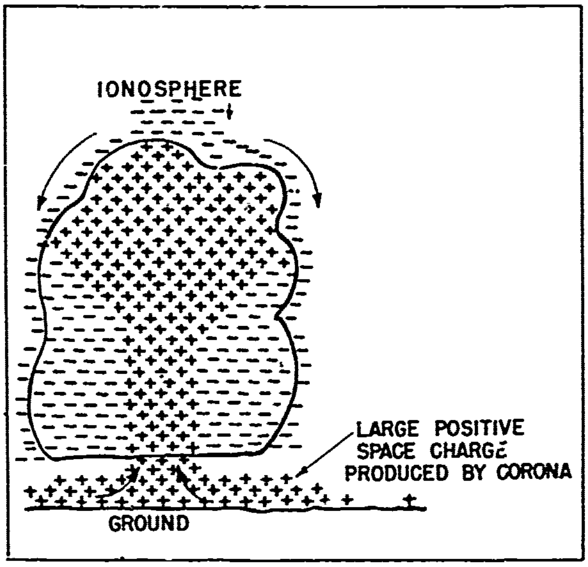


Fig. 3--Intensification of electrification resulting from point discharge on ground

with the considerable body of data that is available on atmospheric electricity, it is possible to make a semiquantitative evaluation of the processes involved in the hypothesis. The following sections are devoted to rough computations of the rate of growth of the charge centers, discussions of the details of the various processes, and speculations upon some aspects of atmospheric electricity.

Observed currents to cloud from ionosphere and ground--Before attempting any calculations of the electrical charging currents that would be expected according to the theory, it is interesting to examine several measurements that indicate the magnitude and direction of the currents flowing above and beneath thunderstorms.

Above the tops of thunderstorms GISH [1951] found that a negative current, frequently of the order of one ampere and sometimes as large as six amperes, flows from the ionosphere to the clouds.

Beneath thunderstorms, the measurements of WORMELL [1930] give evidence that large positive corona currents flow from the ground into the atmosphere. He gives the following estimate of the annual flow of electricity to an area of a square kilometer at Cambridge, England: conduction current, +60 coulombs; point discharge current, -100 coulombs; precipitation current, +20 coulombs; and lightning discharges, -20 coulombs.

These data show that large electrical currents flow toward thunderstorms from the ionosphere and ground in the directions required by the hypothesis. These data also show that the rate at which charge is transferred by these processes is of the same order of magnitude as the rate at which charge is transferred by lightning.

Growth of negative charge center--By making very crude assumptions and simplifications, it is possible to calculate the rate of growth of the charge centers that would be expected according to the hypothesis.

In the first place, let us attempt to estimate the rate at which a cloud formed of positively charged surface air would be able to transport negative charge from the ionosphere down to the lower part of the cloud. In order to do this we must calculate the electric field that exists at the top of the cloud. Let us assume a spherical cloud having a radius r, whose center is r + h above the ground. Neglecting the effect of the Earth and ionosphere, the potential gradient at the surface of the cloud resulting from its space charge is given by

$$F_1 = 6\rho_p r \times 10^{-7} \quad \text{(1)}$$

where F_1 is the gradient in volts per centimeter that would be produced by the cloud alone, r is the radius of the cloud in centimeters, and ρ_p is space charge concentration in elementary charges per cm^3.

At the top of the cloud, this gradient is opposed by the normal gradient in the atmosphere. In order for the cloud to attract negative charge from the ionosphere, it is therefore necessary that the gradient produced by the cloud be greater than this normal gradient. A simple calculation shows that if the positive space charge in the cloud is of the order of ten to 1000 positive elementary charges per cm^3, which various investigators [OBOLENSKY, 1925; BROWN, 1930; GISH, 1951] report for the lower atmosphere, the cloud does not need to be very large to satisfy this condition. For example, we can calculate the normal gradient in the atmosphere F_2 from GISH'S [1951] data on the conductivity of the atmosphere. From altitudes of 6 km to 15 km, his data can be approximated as follows

$$R = 3 \times 10^{26}/Y^2 \quad \text{(2)}$$

where R is the electrical resistivity in ohm-centimeters and Y is the altitude in centimeters. If we assume an ionosphere-to-ground current of 10^{-16} amperes/cm^2 [CHALMERS, 1949], then the normal potential gradient is given by IR, or

$$F_2 = IR = 3 \times 10^{10}/Y^2 \quad \text{(3)}$$

At an altitude of three km, according to this equation, the normal gradient is 0.3 volt/cm. From (1), a cloud containing a space charge of 100 unit charges per cc would have to be only 50 m in radius in order to neutralize this field. If the space charge density were ten elementary charges per cm^3, the cloud would have to be 500 m in radius. It is evident that the normal electric field of the Earth is so small in relation to the field produced by large clouds that to a first approximation it can be neglected. Accordingly, we will assume that the field at the top of a growing cloud is given by (1).

As the result of the action of this field, negative ions flow from the ionosphere toward the surface of the cloud. If there were no downdrafts on the surface of the cloud or winds above it, the field produced by the cloud would rapidly be neutralized by the space charge of the negative ions that are drawn to its surface. However, visual observations and lapse-time motion pictures made by Schaefer and others show that a cumulus cloud is much like a large fountain of hot air with an updraft in the center and strong downdrafts over the surface all around. These downdrafts remove the negative charges on the surface of the cloud and carry them down to lower levels, where they accumulate to form a charge center. Because the downdrafts carry away the layer of negative space charge as fast as it forms, the positive field of the cloud is not completely neutralized and a current of negative ions flows continuously from the ionosphere to lower levels.

The structure of these downdrafts appears to be quite complicated. It is a very difficult matter to estimate at what rate they remove the negative space charge around the top of the cloud and to what extent the field of the cloud is reduced by this space charge. We will make the simplest assumption: that at the top surface of the thundercloud, the actual field can be expressed by a factor α times the value that the field would have in the absence of the negative space charge. The factor α will obviously depend on the downdraft velocity. If this velocity were very large, very little space charge could accumulate on the top of the cloud, so that α would approach one. In the absence of

downdrafts, α would become zero. It is probable that α depends not only on the downdraft velocities but also on other variables such as the shape and size of the cells in the cloud.

However, if we assume that the gradient at the surface of the cloud can be expressed by

$$F = 6\rho_p \alpha r \times 10^{-7} \quad \ldots \quad (4)$$

and assume that all of the negative charge flowing from the ionosphere is accumulated as a charge center at intermediate levels, then it is possible to compute the magnitude of this negative current, I_n, by dividing the gradient by the expression for the electrical resistance of the air and multiplying by the surface area of the cloud top.

Eq. (2), which is based on Gish's data, is for the positive resistivity of the air. This can be converted to give negative resistivity by multiplying by the factor 0.78, the ratio of the mobility of positive to negative ions [GISH, 1951]. Using this we obtain

$$I_n = 8\alpha\rho_p r^3 (2r + h)^2 \times 10^{-33} \text{ amperes} \quad \ldots \quad (5)$$

or if r is large with respect to h

$$I_n = 3\alpha\rho_p r^5 \times 10^{-32} \quad \ldots \quad (6)$$

If we assume that the radius of the cloud increases linearly with time at a rate v, then the current as a function of time is given by

$$I_n = 3\alpha\rho_p v^5 t^5 \times 10^{-32} \quad \ldots \quad (7)$$

The charge Q_n that has built up can be expressed as a function of time by integrating (7) to give

$$Q_n = 5\alpha\rho_p v^5 t^6 \times 10^{-33} \quad \ldots \quad (8)$$

If V is 500 cm/sec, then

$$Q_n = 1.5\alpha\rho_p t^6 \times 10^{-19} \quad \ldots \quad (9)$$

This expression shows that the proposed mechanism leads to a rapid build-up of negative charge in the lower part of the cloud.

Figure 4, a graph based on this equation, shows how Q_n, the negative charge, and Q_p, the positive charge, might be expected to vary with time or the cloud size when various assumptions are made concerning ρ_p, the positive space charge density in the air forming the cloud, and α the constant which relates the gradient at the cloud surface to the value the gradient would have in the absence of negative space charge. Two curves are shown for Q_n, one for which $\alpha\rho_p$ equals ten and the other for which $\alpha\rho_p$ equals 100. Because the charge Q_n depends on the sixth power of the time or cloud size, the time necessary to build up a given charge is not particularly sensitive to assumptions made concerning ρ_p and α, as it occurs as their sixth root. It should be remembered that Figure 4 and the calculations made thus far are based on the assumption that the positive space-charge density in the cloud is of the same order of magnitude as that found in the lower atmosphere. It will be shown later that when the negative charge reaches a certain value, corona discharge from points on the ground will greatly increase the positive space charge density in the air entering the cloud and thus cause the charges to build up more rapidly.

It is worth pointing out that according to the hypothesis there are conditions under which even a very large cloud would not be expected to produce lightning. For example, it will be remembered that in the derivation of (4) it was assumed that ρ_p was sufficiently large that the normal gradient

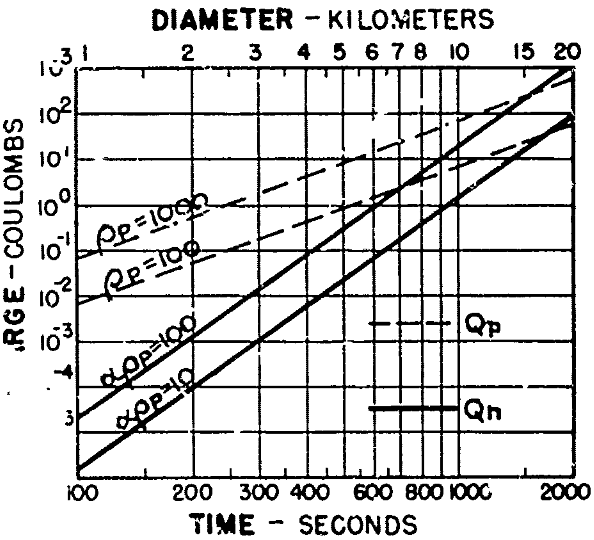


Fig. 4--Estimated charge growth without point discharge

in the atmosphere was negligible in comparison with that produced by the cloud. If the value of ρ_p is quite small, perhaps of the order of one or less elementary charges per cc, this assumption is no longer true, and the cloud may never grow big enough to overbalance the normal field. In this case, the process of drawing negative charge from the ionosphere would not take place.

Even a very large cloud having an appreciable space charge density may still fail to develop electrical activity if the negative charge attracted to its surface is not removed and accumulated as a charge center. This would be the case if there were very small downdrafts on the cloud, which would mean that α is very small, or if high winds at the top of the cloud continuously removed the negative charge and, instead of gathering it as a charge center, merely carried it away.

Growth of positive-charge center--According to the hypothesis, when the negative charge in the lower portion of the cloud reaches a certain value, the field on the surface of the Earth will become sufficiently large to cause objects on the ground to give corona. WHIPPLE and SCRASE [1936] give the following empirical relation between the electric field and the positive current I flowing per km^2 from point discharge.

$$I = 1.6\,[F^2 - (8.6)^2] \times 10^{-6} \ldots \quad (10)$$

where I is the current in amperes and F the field in volts/cm. According to this expression corona does not begin until the field is 8.6 volts per cm. If we assume that the negative center of charge is about three km above the surface of the Earth, we can compute that the critical field of 8.6 volts per cm would be reached directly beneath the cloud when the negative charge is about 0.4 coulomb. According to Figure 4 this value of the charge would be attained in about 15 minutes when the cloud is nine km in diameter. It is rather difficult to estimate how rapidly positive space charge is being produced and drawn into the cloud as the negative charge rapidly grows. This rate depends on the velocity of air going into the cloud and also on the electric field at the ground, which is the vector sum of the field caused by the negative charge and the field caused by the positive space charge being produced. It simplifies matters if we look at the situation in another ten or 20 minutes when the negative charge has grown to perhaps 50 coulombs and the field on the ground in the absence of positive space charge would be of the order of 1000 volts/cm. According to (10), with this field the corona current per km^2 is of the order of one ampere. We are justified in assuming that when the corona current reaches this magnitude the positive space charge produced near the ground is very nearly equal to the negative charge above. If we assume that the positive space charge beneath the cloud has an area of the order of 100 km^2 and that the wind is flowing radially inward toward the center of the cloud at five meters per second, then in every period of the order of ten minutes an amount of positive space charge almost equivalent to the negative portion of the cloud would be transported into the upper part of the cloud.

Another rough way of looking at the effect of corona is to say that in (8) the density of positive charge in the cloud is no longer constant but begins to increase with Q_n. Since Q_n varies as the sixth power of the time and is also proportional to ρ_p, one might expect that after corona had begun both the negative and positive charges in the cloud would increase as some power of time greater than six.

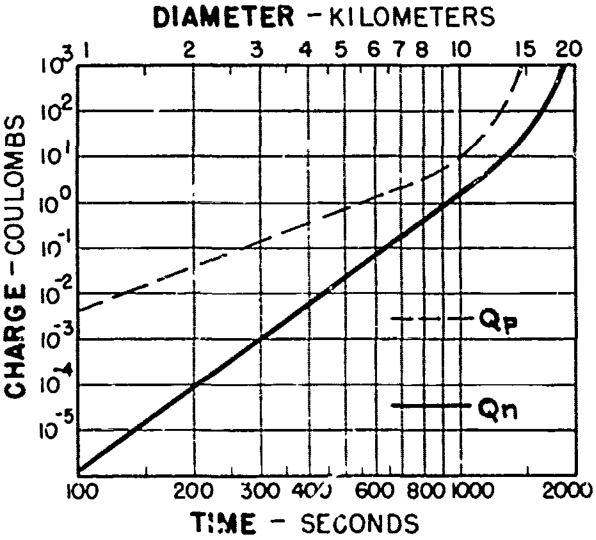


Fig. 5--Estimated charge growth with point discharge

It appears, according to this hypothesis, that the electrical activity in cumulus clouds increases as something like the sixth power or more of their size and that the amounts of charge and the field could become sufficiently large to produce lightning when the cloud is about ten km in diameter or perhaps 25 minutes old.

When the process of corona is taken into account, one might guess that the growth of the charge centers in a cloud might be something like that shown in Figure 5. It should be emphasized that this picture of the build-up of charge is little more than a very rough guess. The rate of charging undoubtedly varies greatly from one cloud to another. For example, if a cloud were to grow to a height of ten km and then stop growing and stay about this size, then the positive-charge center might stop growing while the negative-charge center would continue to increase. The negative-charge center might become considerably larger than the positive center until finally corona would take place that would increase the positive space charge density and cause the positive center to resume its growth. It would be possible to make a more rigorous mathematical approach that would attempt to take into account such factors as the effect on the field around the cloud caused by induced charges in the ground and in the ionosphere, as well as the interaction of the fields of the two main charge centers. However, it appears doubtful whether such refinements could be justified at present in view of the lack of knowledge of many of the important variables characterizing the cloud.

Nature of space charge--If updrafts and downdrafts are to perform electrical work by moving charged particles in an electric field, it is necessary that the velocity of the particles relative to the air that results from electrical forces be somewhat less than the velocities of the updrafts and downdrafts. In the early stages of thunderstorm development, when the fields are small, it is possible that even small ions, which have mobilities of the order of one cm per second per volt per cm, can be moved by the wind against the force resulting from the electric field. However, in the intense fields of a full-fledged storm, it is necessary that the charge-carrying particles have much lower mobilities if they are to be carried by the wind. It is postulated that the small negative ions drawn from the ionosphere, and the small positive ions produced by corona, attach themselves to cloud particles and Aitken nuclei and thus become transformed into ions of low mobility.

Data are not available concerning the concentration and the mobility of the particles comprising the space charge in thunderstorms. However, it is possible to make rough estimates of these quantities. Let us suppose that the charge center in a storm is a sphere having a radius of three km and that the field at its surface is 10^4 volts/cm, a very large field that would probably result in lightning. Using (1) we can compute that the average density of space charge in the cloud is of the order of 5×10^4 elementary charges per cm^3 The total charge of such a cloud is about 10^3 coulomb.

The mobility of the charged cloud particles comprising this space charge can be calculated from their size and concentration on the assumption that the particles carry equal charges. If the cloud particles have a radius of ten microns and the liquid water content is 1 gm/m^3, then there are about 100 particles per cm^3. The charge on each particle is therefore 5×10^2 elementary charges. Using Stokes law we can compute that the mobility of these ions is 2.5×10^{-4} cm/sec volt cm. Even in a field of 10^4 volts/cm these ions would have a velocity of only 2.5 cm/sec relative to the air.

Some of the particles undoubtedly are more highly charged than others. Therefore, the charge is not uniformly distributed as was assumed in the above calculations. It is interesting to compute what the charge and mobility of ten-micron particles would be if they carried the maximum charge they could attain in a field of 10^4 volts/cm. LADENBURG [1930] had given the following relation between the maximum charge Q that can be acquired by a particle of radius a and dielectric constant k in a field F.

$$A = Fa^2 [1 + 2(K - 1)/(K + 1)] \qquad (11)$$

From this equation, it can be calculated that in a field of 10^4 volts/cm, water particles having a radius of 10 microns would each carry 2×10^5 elementary charges and have a mobility of 10^{-1} cm/sec volt cm. The space charge density in a cloud of such particles would be about 2×10^7 elementary charges per cm^3. Even with this large space charge density, the mobility of these particles would still be sufficiently small that they might be moved against strong fields by the high winds in a thunderstorm.

In the region under the cloud the only particles to which the small ions produced by corona can become attached are the Aitken nuclei. These small particles generally carry only one elementary charge apiece and have mobilities of the order of 10^{-3} cm/sec volt cm. The usual concentration of these particles is of the order of 10^4 per cm^3, so that the space charge that can be carried by these particles has a density of the order of 10^4 elementary charges per cm^3. A layer of space charge of this density would have to be 2.5 km thick in order to neutralize a field of 10^4 volts/cm. Thus it appears that in strong fields, if the cloud base were low or if the concentration of nuclei were low, many of the fast positive ions produced by corona might proceed all the way up to the cloud base before being transformed into ions of low mobility.

The concentration of space charge can be estimated in a somewhat different way by calculating the minimum space charge density that would be required in order to produce the charging rates that have been observed in thunderstorms. If we assume that the charging current consists of charged particles being carried by an average wind of 5 m/sec over an area of 100 km^2, then we find that a space charge density of 10^4 elementary charges/cm^3 is required to give a current of four amperes. This value is in fair agreement with the results of the calculation of the charge density that was made using rough guesses for the values of the field and size of a charge center.

It can be concluded from the foregoing speculation upon the concentration and mobility of charged particles in a thunderstorm that quantities of charge ample to produce lightning can be carried in the form of charged particles of low mobility. Although the space charge usually consists of charged-cloud particles, it is conceivable that the electrification process might take place in the absence of cloud particles if a sufficient concentration of Aitken nuclei were present in the atmosphere.

When precipitation particles are present, they too will doubtless constitute a portion of the space charge. They will carry a charge because they have been formed by the coalescence of charged cloud particles or because they have been subjected to the same charging process as the cloud particles.

Loss of charge caused by conduction and mixing--Electrical conduction between the charge centers and the mixing of the air masses carrying charges of opposite signs will reduce the rate at which charge builds up in a thunderstorm. These two processes were neglected in the estimates of the rates of growth of the charge centers.

There are apparently no data on the electrical conductivity within thunderstorm clouds that can be used to estimate the rate at which charge is lost by conduction. CHALMERS [1949] cites data taken by SCRASE [1933] showing that the conductivity in fogs is about one-tenth the normal value for air, and states that in clouds the conductivity is usually very small if no source of

ionization is present. These data are presumably for ordinary clouds and probably do not apply to thunderclouds, which according to the theory must contain a large concentration of charged particles.

In the absence of measurements of the conductivity in thunderstorms, it is possible to estimate the conduction current by using values for the conductivity calculated from the probable space charge. If we assume that the cloud has an average space charge density of 5×10^{-4} elementary charges per cm^3, and the mobility of the ions is 2.5×10^{-4} cm/sec volt cm, then a charge center 3 km in radius having a field of 10^4 volt/cm would have a leakage current over its surface of 2×10^{-2} ampere. This is small compared to the calculated value of the charging current, which is of the order of one ampere for such a cloud.

Because of the complexity of the turbulent mixing within a thunderstorm, and the inadequacy of the available data, one can only make guesses concerning the rate at which charge is lost by mixing. From the appearance of the surface of a thunderstorm cloud, one might guess that the cells of turbulence are generally large enough that their surface-to-volume ratio would be sufficiently small, that mixing would not seriously interfere with the electrification process. It will be necessary to secure much more data before the roles of conduction and mixing can be properly evaluated.

The relationship of lightning to the charging process--Lightning is an important link in the electrical process by which thunderstorms move negative charge from the ionosphere to the Earth. It seems probable that most of the negative charge drawn from the ionosphere according to this theory is transferred to the Earth by lightning strokes. This happens in two different ways. The first of these is a direct process in which the lightning transfers the negative charge to the ground by a cloud-to-ground stroke. The second is an indirect process in which the lightning stroke takes place between the negative charge center and the positive charge center in the cloud. Because the positive charge that is neutralized by a stroke within the cloud was produced by corona from points on the ground, this process effectively transfers negative charge to the ground.

According to the theory, for several reasons it is unlikely that lightning strokes could completely neutralize a thunderstorm. In the first place it has been shown that the two charge centers have different rates of growth. Therefore it is unlikely that they would be equal when lightning occurs. In the second place, in addition to the two primary charge centers there is a large quantity of negatively charged air over the surface of the cloud and a large quantity of positively charged air beneath the cloud. Even if the two primary charge centers were to be completely neutralized by a lightning stroke between them, these secondary masses of charged air would provide sufficient charge to maintain the electrification process.

One would expect that lightning strokes could completely change the normal charge distribution in a cloud. For example, if lightning were to neutralize the negative charge in a cloud, the air at lower levels beneath the cloud would still retain a large positive charge that had been produced by corona. This air, when it is drawn together into the cloud, could, by corona, produce a new region of negative charge near the ground before it is neutralized by lightning. One can imagine situations of this sort in which a cloud conceivably might have an alternating polarity.

Variations of the model--Actual thunderstorms are doubtless far more complex than the simple model shown in Figures 1, 2, and 3. It is interesting to consider the differences between actual clouds and the one used as a model and how they might affect the hypothesis.

In the first place, thunderstorms usually consist of more than one cell. In such storms it is likely that each cell operates in a manner similar to the single cell in the model. In this case there would be downdrafts carrying negative charge not only on the surface of the storm but also within the storm between the cells.

Thunderstorms are seldom as symmetrical as the model. In general, one might expect, because of winds or because of differences in the air masses around the cloud, that updrafts would be predominantly on one side of the cloud, with downdrafts on the other. This should not make much difference in the charge-generating process that has been postulated.

A small cloud probably very seldom grows continuously until it becomes a large one, as has been assumed to be the case. Actually it appears that storms develop by a succession of clouds that rise to some maximum height and then recede, to be followed by other clouds that rise and fall until finally clouds form that reach great heights. In addition to the transfer of charge to lower levels resulting from downdrafts, a large amount of negative charge is probably also brought to lower levels because of the descent of the entire cloud. This process would constitute a sort of pumping action in which negative ions from high altitudes become trapped on cloud particles or Aitken nuclei on the top of the cloud and are then pulled down to lower altitudes by the subsidence of the cloud.

According to the model shown in Figures 1, 2, and 3, the buildup of charge within a storm is brought about by two different processes: (1) the conduction of charge from the ionosphere, and (2) the production of corona from the ground. One can imagine conditions in which only one or the other of these charge-producing processes takes place. For example, over a smooth body of water, or over a land surface devoid of points, it is conceivable that corona might never take place and that the electrification process would occur only at the top of the cloud. One would expect that the negative charge might become much larger than the positive charge and that a greater fraction of the lightning strokes would take place from cloud to ground (or sea) than in a storm over an uneven land surface that gives corona more easily.

If for some reason the space-charge density at lower levels were abnormally large, it is possible that the charge of an electrical storm might be derived exclusively from the Earth by corona. If this condition prevailed, a relatively small cloud at low altitudes would be capable of producing large masses of oppositely charged air by corona. If, because of winds, there were relative motion between the cloud and the air surrounding it, such a cloud might produce masses of air containing many times its own original charge. This air, when drawn into other clouds, might be capable of producing lightning. One can visualize a circulatory process such as that shown in Figure 6 in which two clouds of opposite sign continuously charge each other as the result of corona produced beneath them.

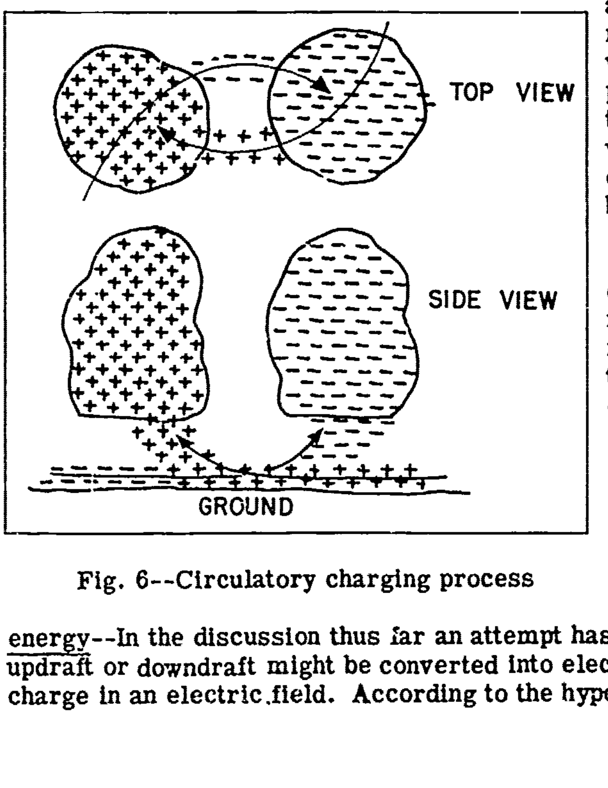


Fig. 6--Circulatory charging process

The electrification process is undoubtedly very complicated in large, intense storms that consist of many cells. Most of the air in such a storm and near it probably becomes highly electrified. Under these conditions, any growing cell would inevitably draw in air masses that are highly charged with one sign or the other. It is to be expected that in large, complex storms clouds will frequently develop with a charge distribution quite different from that normally found in smaller and simpler storms.

Conversion of electrical energy into kinetic energy--In the discussion thus far an attempt has been made to show how the kinetic energy of an updraft or downdraft might be converted into electrical energy because of the movement of space charge in an electric field. According to the hypothesis, once the cloud has become electrified,

there is no reason why the reverse process should not be possible, that is, the conversion of some of the electrical energy in a storm back into kinetic energy through the acceleration in an electric field of air that contains space charge. Indeed, when the cloud draws negative charge from the ionosphere and positive charge from the ground, the air carrying this charge is first accelerated toward the cloud by electrical forces. Only when the wind begins to move these particles away from the charge that induced them and toward the charge of like sign that is building up is the air decelerated.

When the electric field and the space-charge density are small, the forces involved are negligible. However, in an intense electrical storm, the space charge and fields are such that the accelerations resulting from these forces may be large. For example, in a field of 10^4 volts/cm, air that contains a space charge of 10^7 elementary charges per cm^3 will have an acceleration equivalent to that which would result if its temperature were 50°C higher than the surrounding air mass. If the acceleration produced by electrical forces coincides with the directions of the updrafts or downdrafts, some of the electrical energy of the storm will be transformed back into kinetic energy of the air instead of lightning. Through this electrical process, the translational kinetic energy of a large mass of air moving at a moderate velocity can be transferred to a much smaller mass of air that will have a much higher velocity.

This hypothesis suggests that the extreme wind velocities in electrical storms, which can produce hail and tornadoes, may be the result of thermal updrafts that are intensified by electrical forces. This follows the suggestion made by HARE [1840] that the tornado is an electrical phenomenon. The frequently reported buzzing sound associated with the tornado may be caused by intense corona discharge which produces highly charged air near the ground that then is accelerated towards a large region of opposite charge.

It is also possible that the electrical energy in a storm can produce high-velocity updrafts as the result of the heating produced by lightning strokes. FLORA [1953] quotes two different observers who reported that the inside of the tornado appears to be a hollow cylinder illuninated with constant flashes of lightning. It would be expected that the interior of a tornado would offer a low-resistance path for lightning because of its low pressure, and that the heating and ionization produced by lighthing would further lower this resistance. If lightning flashes transporting 20 coulombs per stroke occur within the vortex at the rate of one per second, it can be estimated that the energy would be sufficient to produce an increase of about 100°C in the temperature of a column of air 50 m in diameter rising at 100 m/sec. If only a portion of the electrical energy developed by a large storm were to be converted into kinetic energy by either of these mechanisms, it could supply ample power for a tornado.

<u>The formation of precipitation</u>--According to the generally accepted theory, electrification in a thunderstorm is a result of the formation of precipitation particles. However, the reverse may be true, for, according to the hypothesis set forth in this paper, electrification can take place before any precipitation particles have formed. It is possible that electrification may play a large part in the formation of precipitation both below and above the freezing level. This is in accord with observations such as those made by RAYLEIGH [1875], GUNN [1952], and SARTOR [1953] that suggest that the stability of warm clouds may be influenced by electrical effects, and the experiments made by SCHAEFER [1947, p. 593; 1953, pp. 52-53] that show that the formation and growth of ice crystals is greatly modified by electric fields.

<u>Relationship between charge on ionosphere and thunderstorms</u>--This hypothesis is in accord with the generally accepted theory that the positive charge of the ionosphere is maintained by the electrical activity of thunderstorms all over the world. Furthermore this hypothesis shows how the transfer of negative charge toward the ground might take place by the transport of negative ions in downdrafts and of positive ions in updrafts. It is interesting that according to the hypothesis, the development of electrical activity in a storm depends on the positive ionosphere to produce the small positive space charge that initiates electrical activity.

If the hypothesis is correct, it might be possible to do the following things: (1) Prevent electrical activity in storms locally by neutralizing the space charge in the lower atmosphere. (2) Prevent electrical activity in storms generally by neutralizing the ionosphere. (3) Hasten the onset of electrical activity in storms by increasing the space charge density in the lower atmosphere. (4) Reverse the normal polarity of storms by changing the sign of the space charge in the lower atmosphere.

It is conceivable that the electrical process in the atmosphere is similar to an electrical induction apparatus such as the Wimshurst machine. A machine of this sort that does not employ metal conductors on the rotating plates has three stable modes of operation. One of these is neutral, in which the machine produces no electrical effects, and the other two are those in which a given electrode is either positive or negative, depending on the sign with which the machine was primed. If this analogy holds, the present positive charge of the ionosphere might be fortuitous. It is possible that in the remote past the ionosphere became positively charged, perhaps by intense volcanic activity or dust storms, and that this charge has been maintained since that time by thunderstorms. If the charge of the ionosphere or the space charge in the lower atmosphere were reduced below a certain value, the process might no longer be self-sustaining. If this were to happen, electrical activity would cease and the ionosphere would become neutral. It is also possible that if the ionosphere had a negative charge the atmospheric electrical process might function as it now does, only with a reversed polarity.

Conclusions--The possible merits of this theory of electrification as opposed to the charge separation theory can best be established by measuring the distribution and density of space charge in thunderstorms. If this theory is correct, these measurements should disclose large masses of electrically charged air that are some distance from the region of precipitation, a situation that would be unlikely if precipitation were responsible for electrification. Furthermore, these measurements should show that in both the positive and negative regions of charge, the greater part of the charge is generally in the form of small-charged cloud particles, and Aitken nuclei, rather than precipitation particles. In some cases one might also expect to find that appreciable electric fields had developed before the precipitation particles had formed.

In order to confirm the theory it will be necessary to secure a great deal more data on thunderstorms than are now available and to show quantitatively how these processes can produce the observed electrification.

Acknowledgments--The author is grateful to the many members of the staff of Arthur D. Little, Inc., who have offered suggestions and constructive criticisms that have been of great help in the development of the theory and in the preparation of this paper. The author is particularly indebted to A. G. Emslie, H. O. McMahon, and J. Ulman of this company. In addition, the author wishes to acknowledge very helpful discussions of this subject with H. G. Houghton of the Massachusetts Institute of Technology.

References

BROWN, J. G., Relation of space charge and potential gradient to the diurnal system of convection in lower atmosphere, Terr. Mag. and Atmos. Elec., v. 35, no. 1, 1930.

CHALMERS, J. A, Atmospheric electricity, Oxford Univ. Press and Clarendon Press, 1949.

FLORA, S. D., Tornadoes of the United States, Univ. of Oklahoma Press, 1953.

GISH, O. H., Universal aspects of atmospheric electricity, Compendium of Meteorology, Amer. Met. Soc., pp. 101-119, 1951.

GISH, O. H., and K. L. SHERMAN, Electrical conductivity of air to an altitude of 22 km, Nat. Geogr. Soc. Cont. Tech. Papers, Stratosphere Ser., no. 2, pp. 94-116, 1936.

GUNN, R., The electrification of cloud droplets in non-precipitating cumuli, J. Met., v. 9, pp. 397-402, 1952.

HARE, R., Notices of tornadoes, Amer. J. Sci. Arts, v. 38, pp. 73-86, 1840.

KÄHLER, K., Die electrische Raumladung der Atmosphäre in Potsdam, Met. Zs., v. 44, 1927.

LADENBURG, R., Untersuchungen Über die physikalischen Vorgänge bei der sogenannter elecktrischen Gas reinigung, An. Physik, v. 4, pp. 863-897, 1930.

OBOLENSKY, W. N., Uber elektrische Ladungen in der Atmosphäre, An. der Phys., v. 77, pp. 644-666, 1925.

RAYLEIGH, LORD, Proc. R. Soc., v. 28, p. 406, 1875.

SARTOR, S. D., Coalescence of simulated cloud droplets, thesis, Met. Dept., Mass. Inst. Tech., 1953.

SCHAEFER, V. J., Properties of snow and the electrical effects they produce in storms, Trans. Amer. Geophys. Union, v. 28, pp. 587-614, 1947.

SCHAEFER, V. J., Final report, pt. I, Project Cirrus, General Electric Co., 1953.

SCRASE, F. J., Air-earth current at Kew Observatory, Met. Off. Geophys. Mem. 58, 1933.

WHIPPLE, F. J. W., and F. J. SCRASE, Point discharge in the electric field of the Earth, Met. Off. Geophys. Mem. 68, 1936.

WORMELL, T. W., Vertical electric currents below thunderstorms and showers, Proc. R. Soc. A, v. 127, pp. 567-590, 1930.

SOME REMARKS CONCERNING THE EFFECTIVENESS OF THE LIGETNING ROD AND THE DISTRIBUTION OF LIGHTNING CURRENTS IN THE EARTH

J. Bricard

Institut de Physique du Globe de Paris
Paris, France

Abstract--We calculate, at a given moment, the distribution of lightning currents in the neighborhood of the spot struck by the flash of lightning. One supposes that, during the partial discharge, the current, which flows from the Earth to the cloud, travels over a vertical rectilinear conductor, and has an intensity given by Golde's formula $I = M (e^{-mt} - e^{-nt})$; t being the time, and m and n two constants respectively equal to 4.4×10^4 and 4.6×10^5. We take, as a maximum intensity I_m = 25,000 amp. It is assumed that the Earth is an homogeneous conductor, separated by a plane from the atmosphere. We take the atmosphere as an equally homogeneous dielectric. It is assumed that there is no hysteresis and that, owing to the relative small values of the charges, there is no chemical dissociation in the ground. We transform these conditions into Maxwell's relations written in cylindrical coordinates, owing to the symmetry of the problem. In this case, one can see that the components I_ϕ of the current density and H_x and H_z of the magnetic field are zero. The relations may be simplified, and the displacement term $\epsilon\, dE/dt$ (ϵ represents the dielectric constant and E the electric field in the Earth) may be disregarded when compared to the conductivity term in consideration of the relatively high values of the electric conductivity of the ground ($\sigma = 10^9$ cgs).

Using a particular integral and Carson's method, we obtain equations for I_r, I_z, and H_ϕ. We draw the curves representing the variables in terms of z or r for values included between 10 and 10^4 cgs, and we study in particular the skin effect and the potential distribution under the Earth surface. The results are discussed and compared with experimental values.

Introduction--We assume that in the initial phase of a lightning stroke a conducting channel which has the same potential as a cloud runs from this cloud down to the neighborhood of the ground. A brush discharge emanates from the ground; one branch of this discharge makes contact with the lower extremity of the channel whereupon a discharge rises from the ground in the direction of the cloud (return flash). The ground therefore supplies the charge that neutralizes the charge of the channel and of the cloud. The movement of this charge corresponds to the lightning current. Such a current recurs with each partial discharge, the whole of which forms the lightning stroke. The latter is thus composed of a series of successive pulsations.

The phenomenon appears as if the current were channeled through a vertical conductor from the ground to the cloud. Let us assume that during each partial discharge its intensity I, which varies with time, is represented by the formula

$$I = M (e^{-mt} - e^{-nt}) \qquad (1)$$

established by GOLDE [1948]. In this formula t is the time, and m and n are two constants equal to 4.4×10^4 and 4.6×10^5, respectively. (It should be pointed out that these values are only indications and may vary greatly.) If we take a maximum intensity of 25,000 amp, we obtain an M of nearly 33,000 amp. Since the duration of lightning is extremely short, the outgoing charge in this process does not exceed a few coulombs.

The dimensions of cloud charges are of the order of one kilometer. Displacement currents accompanying the lightning current will be distributed in a volume limited by the base of these

charges and by the Earth's surface, subjected to their influence. The intensity of these currents across a horizontal surface perpendicular to the lightning channel, whose dimensions are small compared to the base of the cloud, may therefore be disregarded in comparison with the intensity of the lightning current. Especially the magnetic field of this current at a point near the ground will yield the relation $H = 2I/r$, in which r is the distance from the lightning channel, and I is given by (1).

Let us consider a vertical lightning rod that is struck by lightning, and let us take as our initial time the moment at which the current surge appears at the base of the rod. Let us next assume that the resistance of the ground plate is zero; therefore, no difference exists between the ground potential and that of the base of the lightning rod.

Let I(t) be the current intensity at this given point. Some researchers [BODIER, 1937] have expressed the belief that the current in the rod differs from that of the lightning, as represented by (1), and that it can be computed from this relation if the reflections produced at the base and the top of the lightning rod as well as the resulting vibrations are taken into account. However, this would lead one to infer that a lightning rod of a given height is able to modify the lightning current that strikes it, the resulting modifications being related to the height of the rod above the ground. This appears quite improbable. Moreover, observations of NORINDER [1947] in open country as well as investigations by McEACHRON [1931] of lightning striking high buildings do not show any disagreement. In a first approximation we will therefore assume that these oscillations, if they exist, are masked and that the entire discharge, including the oscillations, is represented by (1). If necessary, the oscillations could easily be taken into consideration in the computation.

Consequently, the lightning wave rises again in the lightning rod with a propagation velocity of v which is nearly equal to that of light. At height h above the ground, the intensity is $I(t - h/v)$.

Let Z be the wave impedance of the lightning rod, which we may assume to be vertical and rectilinear. Then, $Z \approx \sqrt{L/C}$, where L and C designate the coefficient of self-induction and the linear capacitance of the lightning rod, respectively. This value, which depends upon the size of the conductor as well as upon its height h, is on the average 200 ohms (for h = 20 to 30 m).

At a given moment the absolute value of the potential difference [BRICARD and LEDOUX, 1951] between two points of height h and h + dh, respectively, is

$$dU_1 = L\, dh\, dI/dt = (Z/v)\, dh\, dI/dt$$

where according to (1)

$$dU_1 = (Z/v)\, M\, [ne^{-n(t-h/v)} - me^{-m(t-h/v)}]\, dh$$

At a given moment the potential difference between a point on a conductor of height h and the ground is given by the formula

$$U_1 = MZ\, [e^{-nt}\, (e^{hn/v}-1) - e^{-mt}\, (e^{hm/v}-1)] \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

This relation shows that the absolute value of the potential difference between a point on the lightning rod traversed by a flash of lightning and the ground increases with the elevation of this point. It also shows that the instantaneous potential at the top of a lightning rod is a function of but a single distance, namely, its length, and not the return distance as well (together with the wave reflection from the ground), as has hitherto been assumed.

In addition to this there is the potential drop RI across the ground plate of resistance R, the resulting potential difference being

$$U = RI + MZ\,[e^{-nt}\,(e^{hn/v}-1) - e^{-mt}\,(e^{hm/v}-1)] \qquad (3)$$

For a good ground plate, R = 12 ohms at the beginning of the thunderbolt and then decreases to 1/4 this value after about three microseconds. Let us assume a peak current of 25,000 amp. The maximum value of RI will be 300,000 V for a conductor of height h = 30 m; U will then be of the order of 50,000 V. This value evidently depends on the steepness of the wave front. For a front that is four times steeper (maximum reached in one microsecond) we would obtain 250,000 V. This explains why in most cases the influence of the ground plate remains predominant.

Distribution of lightning currents in the Earth's surface--Let us assume that the Earth is a homogeneous conductor separated from the atmosphere by a plane surface. Moreover, let us also consider that the atmosphere is a homogeneous dielectric and that no hysteresis will take place. Due to the insignificance of the outgoing charge, we need not consider the chemical dissociation. We can introduce these conditions in Maxwell's relations which must be written in cylindrical coordinates in view of the symmetry of the problem.

In this case it is easy to see that the azimuth component E_ϕ of the electric field as well as the components H_z and H_r of the magnetic field are equal to zero. If we give H in electromagnetic units and the rest in electrostatic units we obtain at a specific point of the ground

$$-\frac{1}{c}\frac{\partial H_\phi}{\partial t} = \frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} \qquad (4)$$

$$\frac{1}{c}\left(\epsilon\frac{\partial E_r}{\partial t} + 4\pi\sigma E_r\right) = -\frac{\partial H_\phi}{\partial z} \qquad (5)$$

$$\frac{1}{c}\left(\epsilon\frac{\partial E_z}{\partial t} + 4\pi\sigma E_z\right) = \frac{1}{r}\frac{\partial}{\partial r}(rH_\phi) \qquad (6)$$

In these formulas c is the velocity of light in cgs units ($c = 3 \times 10^{10}$), σ the electric conductivity of the Earth, and ϵ its dielectric constant. The space $z < 0$ corresponds to a dielectric (air) whose constant dielectric and magnetic permeability are both equal to unity. The permeability of the Earth (conductor), for which $z > 0$, is unity. The starting point of the brush discharge, which will finally produce the return flash (or the lightning rod) is taken as the origin of the coordinates. Our position will be far enough from this point to avoid consideration of the arc discharge, whose appearance, moreover, is limited to a zone of a very small radius.

Whatever the shape of the lightning current in the ground, the magnetic field may be expressed as a function of time by a sum of the terms of the form $Me^{-i\omega t}$, the shortest period being of the order of 10^{-6} seconds. The conductivity of the ground is normally of the order of 10^8 to 10^9 cgs; hence we may assume the inequality to be $\omega = (2\pi/T) < 2\pi\ 10^6 \ll \sigma$. The term $\epsilon\,\partial E/\partial t$, corresponding to the displacement current, can therefore be disregarded with respect to the conduction term. Under these conditions (5) and (6) are simplified and become

$$(4\pi/c)\,i_r = -\partial H_\phi/\partial z \qquad (7)$$

$$(4\pi/c)\,I_z = (1/r)\,\partial/\partial r\,(rH_\phi) \qquad (8)$$

Here I_r and I_z are current densities. In order to obtain the I, we first determine H_ϕ from (4), (7), and (8) by eliminating E_r and E_z and obtain

$$(4\pi\sigma/c^2)\,\partial H_\phi/\partial t = \partial^2 H_\phi/\partial r^2 + (1/r)\,\partial H_\phi/\partial r - H_\phi/r^2 + \partial^2 H_\phi/\partial z^2 \qquad (9)$$

According to BLINSKY [1938] the vertical and horizontal current densities are

$$\left.\begin{aligned} I_r &= (M/2\pi r)\,[(r^2/R^3)\,e^{ikR} + (ikz^2/R^2)\,e^{ikR} - ike^{ikz}] \\ I_z &= (Mz/2\pi)\,(1/R^3 - ik/R^2)\,e^{ikR} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (10)$$

with

$$\left.\begin{aligned} R &= \sqrt{r^2 + z^2} \\ k &= (\sqrt{2\pi\sigma\omega}/c)\,(1 + i) = \alpha(1 + i) \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (11)$$

If we consider only the density of the surface current ($z = 0$) and the density of the vertical current passing through the zero point ($r = 0$), we find

$$\left.\begin{aligned} z = 0 \quad I_r &= (M/2\pi r^2)\,[e^{-(\sqrt{2\pi\sigma\omega}/c)r} \cos(\omega t - (\sqrt{2\pi\sigma\omega}/c)\ ) - r\,(\sqrt{2\pi\sigma\omega}/c)\cos\omega t] \\ r = 0 \quad I_z &= (M/2\pi z^2)\,[\ - z\,(\sqrt{2\pi\sigma\omega}/c)\ e^{(-\sqrt{2\pi\sigma\omega}/c)z} \cos(\omega t - (\sqrt{2\pi\sigma\omega}/c)\,z] \end{aligned}\right\} \ldots (12)$$

Near the zero point $I_r = I_z = M/2\pi r^2 = M/2\pi z^2$. There is a spherical distribution of the electric lines as if a direct current were involved. However, this distribution is disturbed, and the skin effect is felt. As we move away from the zero point, I_z decreases in relation to I_r, the more so since the ground is more conducting. Let us make $\sigma = 2 \times 10^9$ cgs and $\omega = 2\pi/2 \times 10^{-6} = \pi\,10^6$. For $z = r = 100$ cm, the term $z\,\sqrt{2\pi\sigma\omega}/c$ is of the order of 0.5.

In reality, above we were dealing with a permanent system. One might ask whether under transient conditions the case would be the same.

Let us assume that H_ϕ is of the form

$$H_\phi = h_\phi\,e^{pt} \quad \ldots\ldots\ldots\ldots (13)$$

where p is a positive constant, independent of time. Eq. (9) may be written

$$(4\pi\sigma/c^2)\,ph_\phi = \partial^2 h_\phi/\partial r^2 + (1/r)\,\partial h_\phi/\partial r - h_\phi/r^2 + \partial^2 h_\phi/\partial z^2 \quad \ldots\ldots\ldots (14)$$

One integral of this equation is given by the expression

$$h_\phi = (2M/cr)\left\{\exp[-(2z/c)\sqrt{\pi p\sigma}] - (z/R)\exp[-(2R/c)\sqrt{\pi p\sigma}]\right\}$$

Under these conditions

$$H_\phi = h_\phi\,e^{pt} = (2M/cr)\left\{\exp[-(2z/c)\sqrt{\pi p\sigma}] - (z/R)\exp[-(2R/c)\sqrt{\pi p\sigma}]\right\}e^{pt} \quad \ldots (15)$$

The term Me^{pt} represents the current passing through the lightning channel. However, the intensity is not of the form Me^{pt} but is represented by (1). It is this form that we must introduce in (15).

The method of CARSON [1929] consists in trying to find the Laplace transform of

$$\exp[-(2z/c)\sqrt{\pi p\sigma}] - (z/R)\exp[-(2R/c)\sqrt{\pi p\sigma}]$$

Let us consider the two terms separately. In fact, we need take only the first term; we may then easily infer the transform of the second.

Let $A(t)$ be the transform corresponding to $\exp[(2z/c)\sqrt{\pi p\sigma}]$. Writing

$$\exp[-(2z/c)\sqrt{\pi p\sigma}/p = \int_0^{\infty} e^{-pt} A(t)\,dt$$

we have

$$(1/p)\exp[-(2z/c)\sqrt{\pi p\sigma}] \doteqdot \begin{cases} 1-\theta(2z\sqrt{\pi\sigma}/2c\sqrt{t}) = 1-\theta(z\sqrt{\pi\sigma}/c\sqrt{t}) & \text{for } t>0 \\ 0 & \text{for } t<0 \end{cases}$$

The quantity $(1/c)\sqrt{\pi\sigma}/t$ is equal to the inverse of one length and θ represents the error function. Likewise

$$(1/p)\exp[-(2R/c)\sqrt{\pi p\sigma}) \doteqdot \begin{cases} 1-\theta[(R/c)\sqrt{\pi\sigma/t} & \text{for } t>0 \\ 0 & \text{for } t<0 \end{cases}$$

with

$$\theta = 2/\sqrt{\pi}\int_0^{(z/c)\sqrt{\pi\sigma/t}} \exp(-u^2)\,du$$

Finally

$$A(t) = (2/cr)\left\{1-\theta[(z/c)\sqrt{\pi\sigma/t}) - (z/R)][1-\theta(R/c)\sqrt{\pi\sigma/t})]\right\} \ldots\ldots\ldots (16)$$

For $t = 0$ $\quad\theta(\infty) = 1\quad A(0) = 0$
$t = \infty\quad\theta(0) = 0\quad A(\infty) = (2/cr)(1 - z/R)$

Having determined the function A(t), the so-called transmission function, we find the value of the field H_ϕ [CARSON, 1929]

$$H_\phi = A(0)I(t) + \int_0^t I(t-v)(\partial A/\partial v)\,dv$$

Since $A(0) = 0$

$$H_\phi = \int_0^t I(t-v)(\partial A/\partial v)\,dv \ldots\ldots\ldots\ldots\ldots\ldots\ldots (17a)$$

where I is the excitation function given by (1). On the other hand,

$$\partial A/\partial v = (2z/rc^2)\sqrt{\sigma}/v^{3/2}\left\{\exp[-(z^2/c^2)\pi\sigma/v] - \exp[-(R^2/c^2)\pi\sigma/v]\right\}$$

hence

$$H_\phi = (2z/rc^2)M\sqrt{\sigma}\int_0^t\left\{\exp[-(z^2/c^2)\pi\sigma/v] - \exp[-(R^2/c^2)\pi\sigma/v]/(t-v)^{3/2}\right\}(e^{-mv} - e^{-nv})dv \quad (17b)$$

We may express this in the form

$$H_\phi = (4M/rc\sqrt{\pi})\left\{[J_1 - (z/R)J_2]e^{-mt} - [J_3 - (z/R)J_4]e^{-nt}\right\} \ldots\ldots\ldots\ldots (18)$$

with

$$\left.\begin{aligned} J_1 &= \int_{(z/c)\sqrt{\pi\sigma/t}}^{+\infty} \exp(-u^2 + mz^2\pi\sigma/c^2u^2)\,du \\ J_2 &= \int_{(R/c)\sqrt{\pi\sigma/t}}^{+\infty} \exp(-u^2 + mR^2\pi\sigma/c^2u^2)\,du \end{aligned}\right\} \ldots\ldots\ldots\ldots (19)$$

(See two additional equations on next page)

$$\left.\begin{aligned} J_3 &= \int_{(z/c)\sqrt{\pi\sigma/t}}^{+\infty} \exp\left(-u^2 + nz^2\,\pi\sigma/c^2u^2\right) du \\ J_4 &= \int_{(R/c)\sqrt{\pi\sigma/t}}^{+\infty} \exp\left(-u^2 + nR^2\,\pi\sigma/c^2u^2\right) du \end{aligned}\right\} \quad (19)$$

(See two additional equations on preceding page)

For $z = 0$, we find $H_\phi = (2M/cr)\,(e^{-mt} - e^{-nt})$.

This expression represents the magnetic field of a rectilinear current in air at distance r from the conductor. $M\,(e^{-mt} - e^{-nt})$ is the intensity in this case. H is expressed in electromagnetic units and M in electrostatic units.

The above relation, together with (7) and (8), enables us to compute the current densities at any point on the Earth's surface. The surface current density I_r (z = 0) and the current density I_z (r = 0) are given by the formula

$$\left.\begin{aligned} I_r &= (M/r^2\pi^{1.5})\,[J_2(r)\,e^{-mt} - J_4(r)\,e^{-nt}] \\ I_z &= (2M/z^2\pi^{1.5})\,[J_2'(z)\,e^{-mt} - J_4'(z)\,e^{-nt}] \end{aligned}\right\} \quad (20)$$

if

$$\left.\begin{aligned} J_2'(z) &= \int_{(z/c)\sqrt{\pi\sigma/t}}^{+\infty} u^2 \exp\left(-u^2 + m\,z^2\,\pi\sigma/c^2u^2\right) du \\ J_4'(z) &= \int_{(z/c)\sqrt{\pi\sigma/t}}^{+\infty} u^2 \exp\left(-u^2 + n\,z^2\,\pi\sigma/c^2u^2\right) du \end{aligned}\right\} \quad (21)$$

Interpretation--Figure 1 represents the variations of J_2, J_4, J_2', J_4' as a function of r or z for $\sigma = 2 \times 10^9$ cgs at times $t = 2 \times 10^{-6}$, 5×10^{-6}, 10^{-5}, and 2×10^{-5} after the beginning of the discharge.

When r or z is very small, $J_2 = J_4 = \sqrt{\pi}/2$ and $J_2' = J_4' = \sqrt{\pi}/4$. Under these conditions we see that I_r and I_z decrease as the inverse of the square of the distance, the process being similar to the case of a direct-current flow in the ground.

The situation differs for larger values of z or r, since these quantities are not constant, and the skin effect intervenes. This becomes all the more pronounced as t increases, especially for J_4 and J_4'. Finally, in (18) and (19) we see that nothing is changed, that is, when the time remains constant, the products $r\sqrt{\sigma}$ or $z\sqrt{\sigma}$ also remain constant. At a given distance from the zero point, the skin effect becomes more perceptible since the ground is a better conductor. Thus the skin effect limits the depth of the current's penetration and retards its flow.

Table 1 gives the results of computations for I_z and I_r for $\sigma = 2 \times 10^9$, which corresponds to a high value for the ground conductivity and to a marked skin effect. I represents the current density computed for a current of a constant intensity equal to the maximum intensity at the moment in question. In view of their complexity, the computations give only an approximate order of magnitude. They have been carried out for horizontal distances and depths not exceeding 10 m. To pursue these computations further is not necessary since with increasing distance currents become too weak for the resulting voltages to have any practical importance.

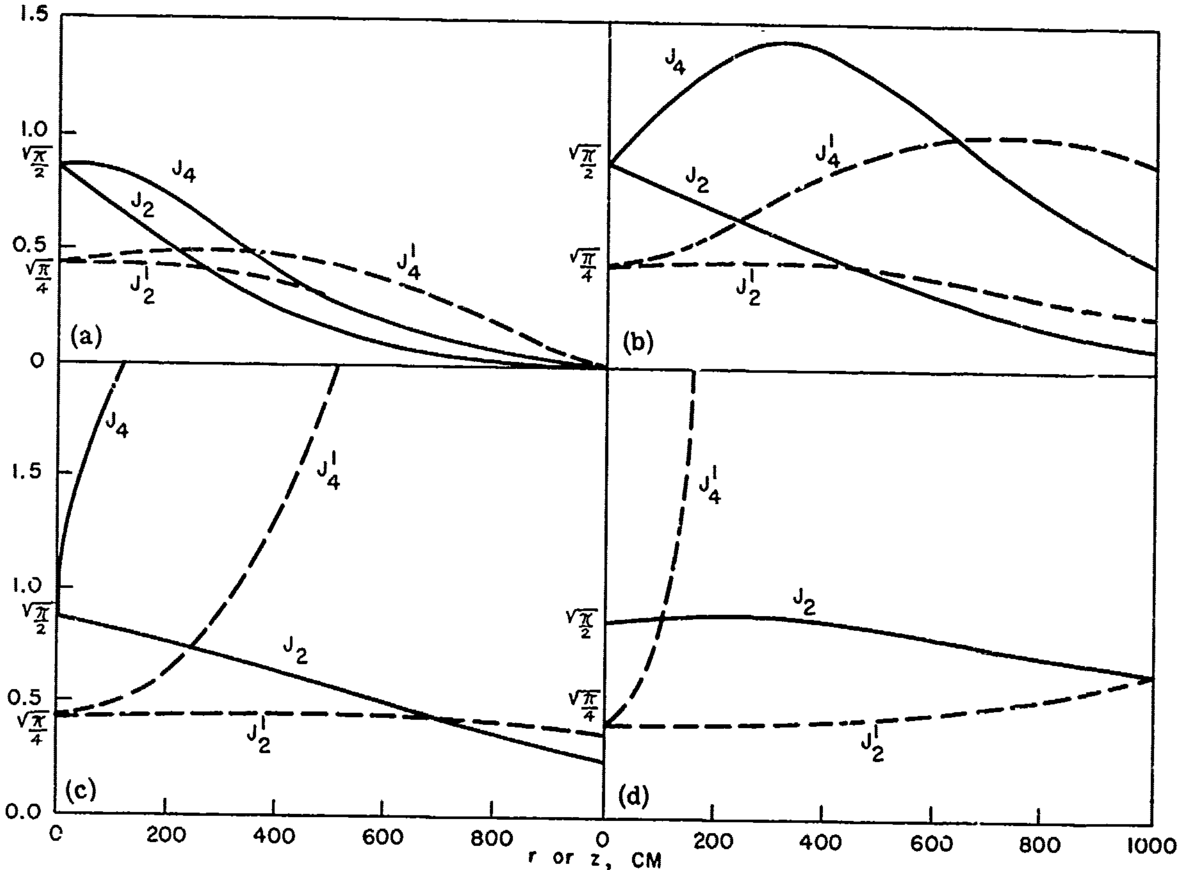


Fig. 1--Variations of J_2, J_4, J_2', and J_4' as a function of r or z, $\sigma = 2 \times 10^9$, (a) $t = 2 \times 10^{-6}$, (b) $t = 5 \times 10^{-6}$, (c) $t = 10^{-5}$, (d) $t = 2 \times 10^{-5}$

In general, the entire process occurs approximately as in the case of a constant current. Deviations appear only for distances greater than one meter and have the effect of decreasing the corresponding intensity by lengthening the duration of the current wave.

Let us assume that the ground has an electric conductivity comparable to that of metals. The electric current flow in the Earth will then be retarded so much that the duration of the lightning wave becomes negligible in comparison with the duration of this flow. Under these conditions we can write (17) in the form

$$H = \int_0^{\tau} I\,(t - \tau)\,(\partial A/\partial t)\,dt = (\partial A/\partial t) \int_0^{\tau} I\,(t - \tau)\,dt$$

where the term $\partial A/\partial t$ can be considered as a constant in the interval 0, τ. The integral represents the total charge Q during the discharge. According to (17b) we will have in this interval

$$H = (2z/rc^2)(\sqrt{\sigma}/t^{1.5}) \left\{ \exp[-(z^2/c^2)\,\pi\sigma/t] - \exp[-(R^2/c^2)\,\pi\sigma/t] \right\} Q$$

where t represents the time computed from the beginning of the discharge. Of course, t is always greater than τ, the duration of the discharge. According to (7) and (8) the density of the surface current I_r and the current density I_z will be given by

Table 1--Values of I_r, I_z, and I for four values of t

z = r	Item	t			
		2×10^{-6}	5×10^{-6}	10^{-5}	2×10^{-5}
cm					
50	I_r	1.08	1.49	1.34	0.707
	I_z	0.908	1.36	1.29	0.712
	I	1.08	1.46	1.33	0.700
$50\sqrt{2}$	I_r	0.535	0.743	0.671	0.354
	I_z	0.421	0.773	0.633	0.357
	I	0.540	0.730	0.660	0.350
100	I_r	0.263	0.370	0.337	0.178
	I_z	0.182	0.309	0.309	0.179
	I	0.270	0.370	0.330	0.170
200	I_r	0.058	0.091	0.085	0.059
	I_z	0.031	0.063	0.071	0.045
	I	0.136	0.185	0.167	0.044
500	I_r	0.004	0.012	0.013	0.008
	I_z	0.003	0.005	0.007	0.005
	I	0.010	0.014	0.013	0.007
1000	I_r	4.8×10^{-5}	0.001	0.002	0.002
	I_z	6.0×10^{-7}	2.0×10^{-4}	7.5×10^{-4}	1.3×10^{-3}
	I	2.6×10^{-3}	3.5×10^{-3}	3.2×10^{-3}	1.7×10^{-3}

$$(4\pi/c)\, I_z = (4z\, \sigma^{1.5}/c^4 t^{2.5})\, \exp\,(-\, z^2\, \pi\sigma/c^2 t)\, Q$$

$$(4\pi/c)\, I_r = (2\, \sqrt{\sigma}/rc^2\, t^{1.5}\, [1 - \exp\,(-\, r^2\, \pi\sigma/c^2 t)]\, Q$$

where $\sigma = 10^{16}$ electrostatic units and $t = 10^{-4}$ sec. I_z is reduced to 1/12 of its value at a depth of one cm, while I_r varies inversely as r as soon as the value of r reaches several centimeters.

References

BILINSKI, S., On the field due to vertical line source of current grounded to Earth, Geophysics, v. 3, pp. 58-62, 1938.

BODIER, G., Sur l'influence du circuit de dérivation au sol des appareils de protection contre la foudre dans un réseau electrique, Conférences Internationales des Grands réseaux Electriques, Rapport 345, 1937.

BRICARD, J., and CH. LEDOUX, A propos de l'efficacité du paratonnerre, An. Geophys., v. 7, p. 275, 1951.

CARSON, E., Régimes transitoires et calsul opérationnel, Extension allemande de Ollendorf et Polhausen, Springer, Berlin, 1929.

GOLDE, R. H., Les courants de foudre dans les lignes de transport, Conférences Internationales des Grands Réseaux Electriques, Rapport 311, 1948.

McEACHRON, K. B., Lightning to the Empire State Building, J. Franklin Inst., v. 227, pp. 149-217, 1939.

NORINDER, H., Some aspects and recent results of electromagnetic effects of thunderstorms, J. Franklin Inst., v. 244, pp. 167-207, 1947.

AN ANALYSIS OF ELECTRIC FIELD AFTER LIGHTNING DISCHARGES

Yuichi Tamura

Geophysical Institute, Kyoto University
Kyoto, Japan

Abstract--The analysis of the electric field after a lightning discharge is based on a following set of simple assumptions. A thundercloud is represented by a vertical dipole of positive polarity. The electrical conductivity of the atmosphere increases exponentially with height, and is not altered by the presence of the thundercloud. The electromotive force in the thundercloud is represented by a constant current generator. It is assumed that an electric field consists of three parts. The first is the field due to charge in each pole which increases at a rate depending on electrical conductivity of the air at a height of the pole; the second, due to space charge which grows with charges in the poles; the third, due to free decaying space charge which is released after a lightning discharge. Characteristic dissimilarity of the form of the field recovery curve, observed after a near discharge to that of distant discharge, is well interpreted by this analysis.

Introduction--One of the most interesting features of the records of the electric field during a thunderstorm is the 'recovery curve' of the field which follows a lightning discharge. Among many types of the field recovery curves [see WILSON, 1921; SCHONLAND, 1928; WORMELL, 1939; TAMURA, 1949], the simplest approximates an exponential form which is usually seen when a discharge is sufficiently distant. The characteristic feature of this simple type has been regarded as an important clue yielding an information about the manner of separation of charges in thunderclouds. A suggestion relating to such simple recovery curve was initially put forward by WILSON [1921] in the following manner. In a thundercloud there presumably exist carriers of opposite electricity having sizes distinctive to the sign of electricity they carry. In the cloud, originally neutral, vertical separation of charges will begin owing to the relative displacement of these carriers under gravity. Under such circumstances the rate of accumulation of charge is not constant, but becomes less as the accumulation progresses, because two kinds of retardation may act; one as an effect of an electric field in the cloud against further accumulation of charges, and the other as dissipation of charges by conduction. Assuming the rate of accumulation, with no retarding effects, to be constant and each retarding effect proportional to charges accumulated, it will be seen that the charges have to increase exponentially with time until a lightning discharge occurs. Further, if the distance between oppositely charged volumes remains unchanged, the charges themselves will be proportional to the electric moment (defined as 2 × charge × distance between opposite charges) of the cloud. Since the electric field intensity, neglecting the fine weather field, observed on the ground at sufficiently remote distance from a storm, is proportional to the electric moment of the cloud, the form of recovery curve of the field is also exponential having a time constant equal to that of charge accumulation. Wilson's suggestion has further been emphasized by WORMELL [1939]. As far as the elementary process of charge generation in thunderclouds is concerned, theory of Simpson differs from Wilson's. They, however, are in agreement with respect to the manner of charge separation [SIMPSON, 1927].

Meanwhile, there is a point of view that the atmospheric electric field be considered as a field accompanying an electric current rather than a static field. This is substantial if the spatial variation of electrical conductivity of the atmosphere is taken into account. In recent years KASEMIR [1950] has discussed various atmospheric electrical phenomena in such atmosphere and has made a remark relating to the recovery curve of a field after a lightning discharge. HOLZER and SAXON [1952] have estimated the electrical conduction current in the vicinity of thunderstorm under equilibrium condition, assuming the atmospheric conductivity increases with height.

In the present paper the analysis of the electric field due to a thundercloud after a lightning discharge is attempted under the assumptions that a simple dipole cloud is imbedded in the atmosphere, the conductivity of which increases with height, as postulated by HOLZER and SAXON [1952]. The analysis is further used in an interpretation of recovery curve of field.

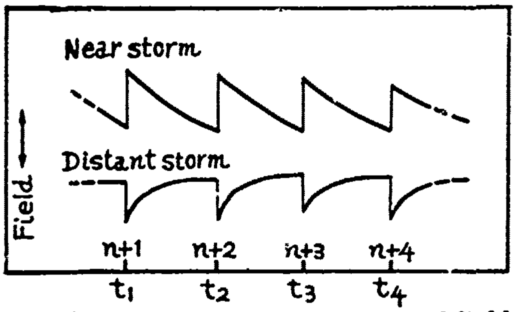


Fig. 1--Schematic representation of field recovery curves

Characteristic features of recovery curves--Records of the electric field at the ground during a thunderstorm of positive polarity in which, as often experienced in the later stage of storm activity, intracloud lightning discharges of similar scale occur repeatedly is schematically represented in Figure 1. At times $t_1, t_2, \ldots$, the n + 1st, n + 2nd, . . . discharges occurred respectively. The upper figure corresponds to a near storm and the lower figure corresponds to a distant storm. In the former case, discharges occur when the electric field is in a diminishing stage and sudden field changes accompanying discharges are positive; while in the latter case, discharges occur some time after the field has attained its stationary value and sudden changes are negative. The definitions of the near and the distant storms are somewhat ambiguous, it may rather be distinguished by the forms of recovery curves. However, consistent with the experience of the writer, the discharges within seven km and beyond 15 km will be called near and distant, respectively. At intermediate distances from discharge there must be a boundary where sudden field changes reverse sign. The field recovery curves at these distances are somewhat complicated. In Figure 2 examples of records of near, intermediate, and distant

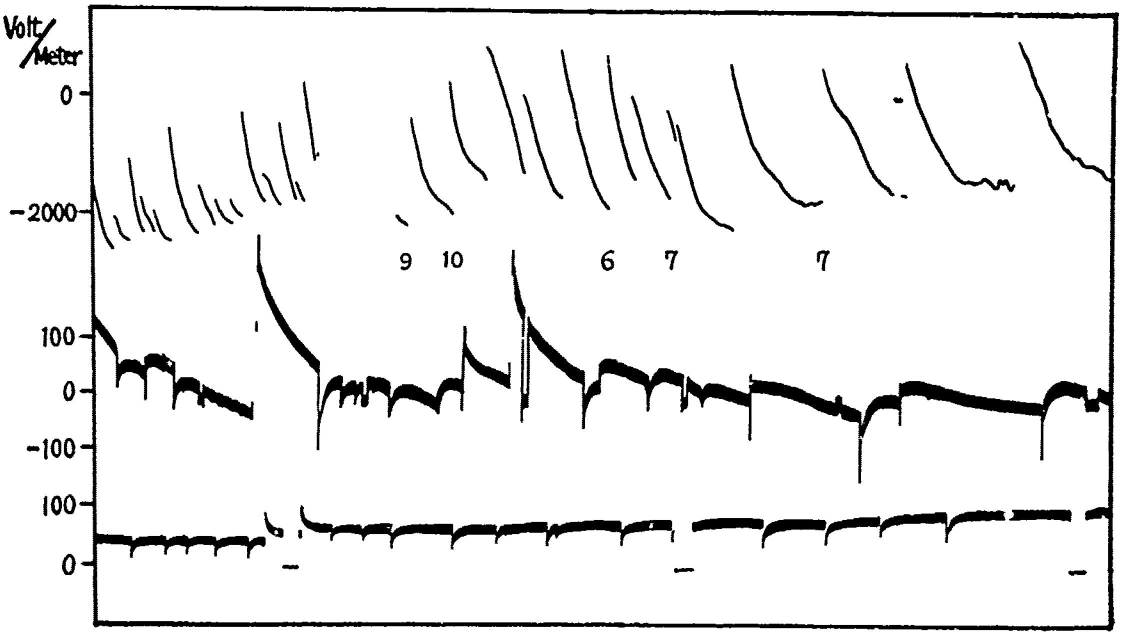


Fig. 2--Examples of electric field of thunderstorms (observed at Kyoto); the upper record is for near storm (16h 10m-16h 34m, Aug. 16, 1944); the values in the record are distances of flashes measured from lightning-thunder interval; the middle is for a storm at intermediate distant (19h 51m-20h 03m, July 25, 1950); thunder was audible; the lower is for distant storm (20h 36m-21h 00m, Sept. 1, 1943); no thunder was heard

storms obtained by means of the rotating collector devised by HASEGAWA [1940] are reproduced. Although they are not the simultaneous records of same flashes, the recovery curves shown are characteristic of the respective distances. Therefore, the correspondence shown in Figure 1 is conclusive.

It is of interest to examine, by employing a simple model of thundercloud and an atmosphere of uniform electrical conductivity, whether the results of observation mentioned above may be interpreted or not. One of the simplest models of a thunderstorm is a vertical dipole of positive polarity, opposite charges being equal in magnitude. The charges are assumed to be distributed uniformly in spherical volumes. In this case the electric field intensity on the ground at sufficiently great distance from a storm, is proportional to the dipole moment. Further, if the charge positions are assumed to be unchanged, the electric field intensity is everywhere proportional to the charge itself. If after a lightning discharge, the charges accumulate exponentially with time, correspondingly after a sudden field change which is positive and negative for near and distant discharge respectively, the field recovery will show an exponential form with a time constant equal to that of charge accumulation. Since these circumstances do not agree with observation in which the recovery curve for near storm clearly is dissimilar to that for distant storm, the simple picture employed above must be abandoned. However, one of the factors affecting the recovery of the field will be mentioned here. It is quite probable that below the base of cloud, a positive space charge may be introduced by a point discharge from the Earth's surface where a strong negative field prevails. The dissipation of this space charge after a lightning stroke may have an important influence on the recovery curve.

On the other hand, the most striking feature of field recovery is that of distant storm, as already mentioned, that a discharge occurs some time after the field on the ground has attained its stationary state. In case the electric field within the cloud grows in direct proportion to the charges in the poles, as assumed here, a discharge will occur when the field intensity reaches the critical value, that is, the charge in the poles accumulates up to a limiting value. It is quite likely that this condition, in general, will be attained when accumulation of charges is going on and not at the state when accumulation of charges has ceased. Conditions of initiation of lightning discharge may be quite delicate, that is, heterogeneous distribution of charge may strengthen a local electric field sufficiently large to initiate a discharge even when the general tendency of the field is still unfavorable for a discharge. However, it is very difficult to expect that discharge occurs some time after the electric field intensity, or the accumulation of charges has reached the stationary state. For, from statistical point of view, the general circumstance of the field will determine the chance of the initiation of a discharge allowing a certain fluctuation depending on the heterogeneity in the field. Therefore, because atmospheric conductivity is assumed uniform, a serious difficulty lies in employing a simple model of cloud. If, however, at the later stage of charge accumulation, an assumption is made that the polar distance varies so as to keep the electric moment constant instead of the polar distance constant, then electric field intensity at remote distances from a storm will have attained its stationary value in spite of the fact that the field within cloud is still growing towards the sparking limit. Since the characteristic feature of the field recovery curve for a distant storm may be interpreted to some extent, this tentative way of thinking is not developed here.

Meanwhile, many years ago, an important factor relating to escape of charge from thunderclouds was pointed out by WILSON [1921]. He stated that in a bipolar cloud, rate of dissipation of upper charge will be larger than that of lower charge on account of the atmospheric conductivity is larger at the top of cloud than at the bottom; especially he suggested that the strong electric field at the top of thunder cloud (being assumed to be positive polarity) may drag down negative ions from the upper conducting layer to make the conductivity of the atmosphere much greater than fine weather value. Although recent observations carried out by GISH and WAIT [1950] showed Wilson's suggestion does not hold and that atmospheric conductivity over the top as well as in the vicinity of thunderclouds do not differ from that of fine weather, it may certainly be said that the thundercloud is immersed in the atmosphere whose conductivity monotonical increases up to a layer higher than the top of thunderclouds. Also, WORMELL [1939], in his detailed discussions on the recovery of the electric field after a lightning discharge, has remarked that dissipation of the charges will

not in general be the same for both charges. But he did not further discuss its effect on the recovery of the field.

According to the writer's opinion, one way possible to interpret the characteristic features of field recovery, which have been emphasized above, is to take account of non-uniform atmospheric conductivity instead of uniform, as GUNN [1935] and HOLZER and SAXON [1952] employed in their studies on electrical phenomena of thunder storms. In these circumstances, space charge outside the poles should play a role on the electric field. In the following paragraphs an analysis of the electric field after lightning discharges is attempted from this standpoint.

Model of a thundercloud, and assumptions--The analysis is based on a following simple model of a thundercloud, and fundamental assumptions. In Figure 3, A and B represent positive and negative poles of a thundercloud respectively forming a vertical dipole fixed in the atmosphere. A′ and B′ are the image of A and B respectively. Separation of electricity is assumed to be constant rate, that is, electromotive force is equivalent to a constant current generator terminals of which are A and B. The electrical conductivity of the atmosphere is assumed to increase exponentially with height and not to be altered by the presence of thundercloud.

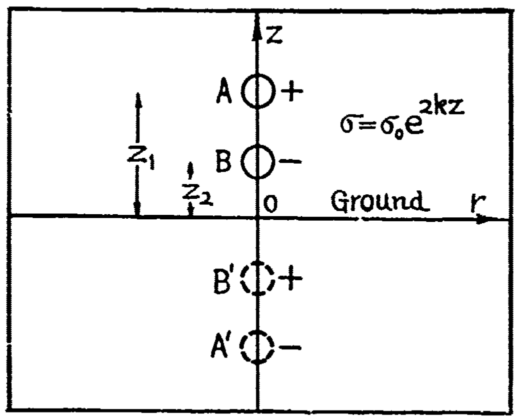


Fig. 3--The model of thundercloud

The coordinate system employed is cylindrical (r, z); the upwardly directed axis of the dipole is taken as z-axis and its intersection with ground is taken as the origin, centers of A and B being $(0, z_1)$ and $(0, z_2)$ respectively. Dimension of A and B are assumed small relative to z_1 and z_2.

Effect of the upper conducting layer which is found as high as several tens kilometers above ground is ignored, and the normal fine weather electric field is also ignored.

Analytical treatment--As the equation to be solved is, as shown later, linear in form, it may be treated, conveniently, in the case of a single pole; when two poles are present the solution is given by superposition of the solution for each pole.

At first, total charge Q as a function of time t, in the positive pole will be considered. Let J_0 be total current supplied to the pole, assumed constant. The total conduction current from the pole to the atmosphere will depend on the electric field intensity as well as on the conductivity at the surface of the pole. But, as the dimension of the pole is assumed small relative to its height, the effective conductivity may be represented by σ_1 which is the conductivity at the height z_1. Then, putting $\lambda_1 = 4\pi\sigma_1$ and $Q_s = J_0/\lambda_1$

$$Q = Q_i e^{-\lambda_1 t} + Q_s(1 - e^{-\lambda_1 t}) \quad \ldots\ldots\ldots\ldots \quad (1)$$

where Q_i and Q_s are initial and stationary value of Q respectively.

The electric field intensity E_{qs} due to Q_s at any point P(z, r) in the atmosphere excluding the region of the pole is represented by its components

$$\left.\begin{aligned} E_{qs,z} &= Q_s[(Z - Z_1)/R^3 - (Z + Z_1)/R'^3] \\ E_{qs,r} &= Q_s r(1/R^3 - 1/R'^3) \end{aligned}\right\} \quad \ldots\ldots\ldots \quad (2)$$

where $R = [(Z - Z_1)^2 + r^2]^{0.5}$ and $R' = [(Z + Z_1)^2 + r^2]^{0.5}$, if variation in conductivity is neglected. Similarly, field intensity E_{qi} due to Q_i is

$$\left.\begin{aligned} E_{qi,z} &= Q_i[(Z - Z_1)/R^3 - (Z + Z_1)/R'^3] \\ E_{qi,r} &= Q_i r(1/R^3 - 1/R'^3) \end{aligned}\right\} \quad (3)$$

Therefore, the field intensity E_q due to Q is

$$E_q = E_{qi}e^{-\lambda_1 t} + E_{qs}(1 - e^{-\lambda_1 t}) \quad (4)$$

Let i be conduction current density, E electric field intensity, ρ space charge density and σ conductivity of the air. Then following relation hold at any point P(z, r) in the atmosphere except the pole under consideration

$$\mathrm{div}\ i = -\partial\rho/\partial t \quad (5)$$

since $i = \sigma E$ and $\mathrm{div}\ E = 4\pi\rho$

$$\mathrm{div}\ (\partial E/\partial t + \lambda E) = 0 \quad (6)$$

where $4\pi\sigma$ is replaced by λ.

Special integral of equation (6) is

$$\partial E/\partial t + \lambda E = 0 \quad (7)$$

Eq. (7) is satisfied by

$$E = E_i e^{-\lambda t} \quad (8)$$

showing that the initially existing field decays as $e^{-\lambda t}$.

General integral of (6) is

$$\partial E/\partial t + \lambda E = \lambda E_\alpha(Z, r, t) \quad (9)$$

where E_α is arbitrary vector satisfying the relation $\mathrm{div}\ \lambda E_\alpha = 0$, and must be determined so that E satisfies the initial and final conditions as well as boundary conditions in the problem. These conditions are as follows:

(1) at $t = 0$, $E = 0$ and $\partial E/\partial t = \lambda_1 E_{qs}$; this condition means if there is no initial field, consequently no charge is found anywhere, the initial rate of field change must be determined by the initial rate of charge accumulation in the pole; (2) at $t \to \infty$, $E \to E_s$ (E_s is the final value of E); and (3) at any time, E must be vertical at the ground and vanishes at infinity, and the relation $Q = Q_s(1 - e^{-\lambda_1 t})$ always hold at the pole.

Then E_α is found as

$$\lambda E_\alpha = \lambda E_s(1 - e^{-\lambda_1 t}) + \lambda_1 E_{qs} e^{-\lambda_1 t} \quad (10)$$

where E_{qs} is given by (2).

From (9) and (10)

$$\partial E/\partial t + \lambda E = \lambda E_s(1 - e^{-\lambda_1 t}) + \lambda_1 E_{qs} e^{-\lambda_1 t} \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Eq. 11 is satisfied by

$$E = E_s\left\{1 - e^{-\lambda_1 t} + [\lambda_1/(\lambda_1 - \lambda)](e^{-\lambda_1 t} - e^{-\lambda t})\right\} - E_{qs}[\lambda_1(\lambda_1 - \lambda)](e^{-\lambda_1 t} - e^{-\lambda t}) \ldots\ldots (12)$$

If at $t = 0$, $E = E_i$, solution of (11) is

$$E = E_i e^{-\lambda t} + E_s\left\{1 - e^{-\lambda_1 t} + [\lambda_1/(\lambda_1 - \lambda)](e^{-\lambda_1 t} - e^{-\lambda t})\right\} - E_{qs}[\lambda_1/(\lambda_1 - \lambda)](e^{-\lambda_1 t} - e^{-\lambda t}) \ldots (13)$$

putting $E_s = E_{qs} + E_{\rho s}$, where E_{qs} is the field intensity due to the charge in the pole at its stationary state, and $E_{\rho s}$ is the field intensity due to space charge in its stationary distribution; (13) is conveniently expressed in the other form as

$$E = E_{qs}(1 - e^{-\lambda_1 t}) + E_{\rho s}\left\{1 - e^{-\lambda_1 t} + [\lambda_1/(\lambda_1 - \lambda)](e^{-\lambda_1 t} - e^{-\lambda t})\right\} + E_i e^{-\lambda t} \ldots\ldots\ldots (14)$$

Eq. (13) or (14) is general result of the present analysis indicating, as (14) shows, that the electric field consists of three parts; the first is the field due to charge in the pole, the second is the field due to space charge, and the third is the free decaying field. E_s the final value of the field intensity is obtained from the relation

$$\mathrm{div}\ \lambda E_s = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Using the fundamental assumption of the conductivity of the atmosphere, that is $\sigma = \sigma_0 e^{2kZ}$, (15) becomes

$$\mathrm{div}\ E_s + 2kE_{s,z} = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

where $E_{s,z}$ is vertical component of E_s.

This is equivalent to the equation which HOLZER and SAXON [1952] have derived and solved, namely

$$\nabla^2\phi + 2k\ \partial\phi/\partial Z = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

where ϕ is potential of E_s.

The solution of this equation to fit the present aim is

$$\phi = Q_0 e^{-k(Z-Z1)}(e^{-kR}/R - e^{-kR'}/R') \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

then the electric field intensity E_s is easily obtained.

Putting $z = 0$ and $\lambda = \lambda_0$, $(\lambda_0 = 4\pi\sigma_0)$ in (13), electric field intensity at the ground is given by

$$E = E_i e^{-\lambda_0 t} + E_s\left\{1 - e^{-\lambda_1 t} + [\lambda_1/(\lambda_1 - \lambda_0)](e^{-\lambda_1 t} - e^{-\lambda_0 t})\right\} - E_{qs}[\lambda_1/(\lambda_1 - \lambda_0)](e^{-\lambda_1 t} - e^{-\lambda_0 t}) \ (19)$$

with

$$E_s = (-\partial\phi/\partial Z)_{Z=0} = -2Q_s e^{-k(R-Z_1)}[kZ_1/R^2 + Z_1/R^3] \ldots\ldots\ldots\ldots\ldots (20)$$

$$E_{qs} = -2Q_s\ Z_1/R^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (21)$$

where $R = (r^2 + z_1^2)^{0.5}$.

Corresponding to (14), (19) becomes

$$E = E_{qs}(1 - e^{-\lambda_1 t}) + E_{\rho s}\left\{1 - e^{-\lambda_1 t} + [\lambda_1/(\lambda_1 - \lambda_o)](e^{-\lambda_1 t} - e^{-\lambda_o t})\right\} + E_i e^{-\lambda_o t} \quad \ldots . (22)$$

Numerical calculations--Numerical values are taken as: $z_1 = 7$ km, $z_2 = 5$ km, the height of positive and negative pole respectively; $\sigma_1 = 1.8 \times 10^{-3}$ esu, $\sigma_2 = 1.2 \times 10^{-3}$ esu, the conductivity of the atmosphere at the height 7 km and 5 km respectively, assuming $\lambda_o = 4 \times 10^{-4}$ esu and k = 0.11 per km; and Q_s are 80 coulombs and -120 coulombs for upper and lower poles respectively, assuming J_o = 1.81 ampere.

Calculations are confined to the electric field at the ground, because only ground observations are used for comparison.

Stationary state: The electric field intensity at a stationary state E_s, which must be attained if no lightning discharge occurs, is calculated from (20); E_{qs}, the field intensity due to charge Q_s, is calculated from (21); then $E_{\rho s} = E_s - E_{qs}$ is the field due to space charge in stationary state. These magnitudes at various distances from the origin are given in Table 1.

Table 1--Stationary electric field intensities at various distances

r	Q_s = 80 coulombs at z_1 = 7 km		Q_s = -120 coulombs at z_2 = 5 km	
	E_{qs} (v/m)	E_s (v/m)	E_{qs} (v/m)	E_s (v/m)
km				
0	294×10^2	520×10^2	-864×10^2	-134×10^3
4	192×10^2	324×10^2	-411×10^2	-601×10^2
8	838×10	122×10^2	-129×10^2	-161×10^2
12	376×10	444×10	-492×10	-496×10
16	189×10	174×10	-229×10	-179×10
20	107×10	744	-124×10	-721
25	576	273	-652	-260
30	344	110	-384	-102
40	150	204×10^{-1}	-165	-185×10^{-1}
50	783×10^{-1}	476×10^{-2}	-850×10^{-1}	-384×10^{-2}

It will be worth while to note that space charge strengthens E_{qs} near the storm and weakens it at great distances, this effect is very large at great distances.

Rising state: Electric field intensity in the rising state is calculated from (22). Examples of these magnitudes varying with lapse of time are given in Table 2. In these calculations the initial field is assumed to be zero. The corresponding magnitudes of E_q are also given in the table.

The following will be noted. If the case of single pole is considered, the effect of space charge on the electric field is not negligible even in the earlier stage of charge separation; while the case of two poles forming a dipole, space charge does not affect the electric field much. Therefore, it may be said, at least in the earlier stage of charge separation, the electric field due to a dipole is determined as if the dipole were in the atmosphere of uniform conductivity. It is important, however, to remember that each pole has charge of opposite sign, but in general of different magnitude.

Field recovery curves: To obtain field recovery curves which are the graphical relation of electric field intensity versus time after a lightning discharge, numerical values given in Table 2 are available. However, it is necessary to make some assumptions as follows: (1) lightning discharges occur between charges in the upper and lower pole; no cloud-ground discharge nor lightning

Table 2--Electric field intensities (v/m) versus time (second)

	at r = 0 km					at r = 50 km				
t	E_{q+}	E_+	E_{q-}	E_-	E	E_{q+}	E_+	E_{q-}	E_-	E
0	0	0	0	0	0	0	0	0	0	0
10	5970	6130	-12100	-12400	-6300	15.90	15.38	-11.90	-11.41	3.97
20	10700	11200	-22600	-23300	-12100	28.52	26.83	-22.16	-20.94	5.89
30	14500	15400	-31500	-32900	-17500	38.62	35.60	-31.03	-28.67	6.93
40	17500	19100	-39100	-41600	-22500	46.67	41.59	-38.51	-34.29	7.30
50	19900	22100	-45800	-49500	-27400	53.09	45.81	-45.05	-38.80	7.01
60	21800	24800	-51400	-56300	-31500	58.18	48.47	-50.58	-42.22	6.25
70	23400	27100	-56400	-62600	-35500	62.25	50.18	-55.42	-44.86	5.32
80	24600	29100	-60600	-68100	-39000	65.46	50.96	-59.59	-46.78	4.18
90	25600	30800	-64100	-73000	-42200	68.12	51.21	-63.16	-47.96	3.25
100	26400	32400	-67200	-77500	-45100	70.16	50.74	-66.22	-48.70	2.04
110	27000	33700	-70000	-81700	-48000	71.80	50.00	-68.85	-48.85	1.15
120	27400	34800	-72200	-85300	-50500	73.13	49.08	-71.06	-48.76	0.32

E_{q+} represents the field due to the positive pole, E_+ represents the field due to the positive pole with space charge accompanying it; E_{q-} and E_- are corresponding fields for negative pole; $E(= E_+ + E_-)$ is the resultant field.

towards atmosphere occurs; (2) in a lightning discharge half of the total positive charge in the upper pole and a corresponding negative charge in the lower pole are neutralized; (3) space charge outside the poles is not affected by a lightning discharge; (4) lightning discharges occur with a constant time interval, this is the time taken for accumulation of positive charge to a specified quantity.

Together with above assumptions, the following remarks become important. It can be said in (22), the electric field intensity due to space charges, namely $E_\rho = E_{\rho s}\{1 - e^{-\lambda_1 t} + [\lambda_1/(\lambda_1 - \lambda_0)](e^{-\lambda_1 t} - e^{-\lambda_0 t})\}$, always h[illegible] accompany that due to charge in pole, namely $E_q = E_{qs}(1 - e^{-\lambda_1 t})$. Therefore, when a discharge o[illegible]t $t = \tau$, if $E_q = E_{qs}(1 - e^{-\lambda_1 t})$ changes suddenly to $E_q' = E_{qs}(1 - e^{-\lambda_1 \tau_0})$, where $\tau > \tau_0 \geq 0$, t[illegible] generation of E_q thereafter will be represented by

$$E_q = E_q' e^{-\lambda_1(t-\tau)} + E_{qs}[1 - e^{-\lambda_1(t-\tau)}] = E_{qs}[1 - e^{-\lambda_1(\tau_0 + t - \tau)}] \quad \ldots\ldots\ldots (23)$$

Consequently, at the instant of the flash, $E\rho$ is divided into two parts; the one is accompanying E_q, and the other, the free decaying part. They are

$$E_\rho = E_{\rho s}\left\{1 - e^{-\lambda_1(\tau_0 - \tau + t)} + [\lambda_1/(\lambda_1 - \lambda_0)][e^{-\lambda_1(\tau_0 - \tau + t)} - e^{-\lambda_0(\tau_0 - \tau + t)}]\right\} \quad \ldots (24)$$

$$E_{free} = E_i' e^{-\lambda_0(t-\tau)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

where

$$E_i' = E_{\rho s}\left\{e^{-\lambda_1 \tau_0} - e^{-\lambda_1 \tau} + [\lambda_1/(\lambda_1 - \lambda_0)](e^{-\lambda_1 \tau} - e^{-\lambda_1 \tau_0} - e^{-\lambda_0 \tau} + e^{-\lambda_0 \tau_0})\right\}$$

Putting $t' = t - \tau$, after the discharge E is represented by

$$E = E_{qs}[1 - e^{-\lambda_1(\tau_0 + t')}] + E_{\rho s}\left\{1 - e^{-\lambda_1(\tau_0 + t')} + [\lambda_1/(\lambda_1 - \lambda_0)][e^{-\lambda_1(\tau_0 + t')} - e^{-\lambda_0(\tau_0 + t')}]\right\}$$
$$+ E_i e^{-\lambda_0(\tau + t')} + E_i' e^{-\lambda_0 t'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (26)$$

In practical calculations it is convenient to select the instant of a flash as a new origin of time, consequently initial conditions must be selected such as, at $t' = 0$, $E = E_i e^{-\lambda o \tau} + E_i'$.

Now recovery curves of the field will be found as illustrated in Figure 4 (this corresponds to the case of the field at r = 50 km, the lightning interval is about 74 sec and there is no field initially).

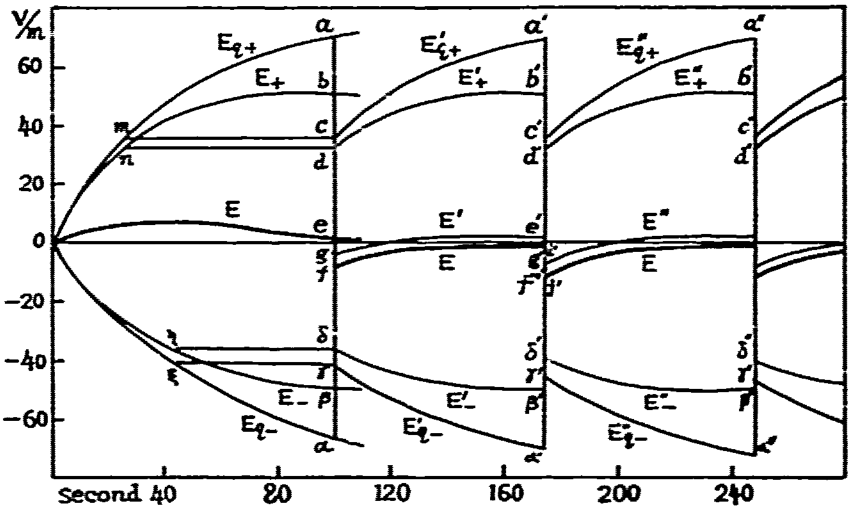


Fig. 4--Method of drawing field recovery curves

Curves E_{q+} and E_+ represent the electric field due to the positive pole and that due to the positive pole with space charge accompanying it respectively (see (22)); curves E_{q-} and E_- represent corresponding fields for the negative pole; curve E represents the resultant field ($E_+ + E_-$).

It is assumed that half of positive charge in the upper pole and corresponding negative charge in the lower pole are neutralized at t = 100 sec. Then, E_{q+} changes from a to c, correspondingly E_{q-} changes from α to γ ($\overline{\alpha\gamma} = (85/1.5 \times 78.3) \times \overline{ac}$, referring to Table 1). Consequently E changes from e to f ($\overline{ef} = \overline{ac} - \overline{\alpha\gamma}$). After the discharge each field which was formerly represented by E_{q+}, E_+, E_{q-}, and E_- will grow along E'_{q+}, E'_+, E'_{q-} and E'_- respectively in the same manner as if the former started from m, n, ξ and η respectively. The resultant field $E'(= E'_+ + E'_-)$ will grow starting from g. The magnitude of electric fields released by the discharge of positive and negative charges in the poles are $\overline{cd} - \overline{ab}$ and $\overline{\alpha\beta} - \overline{\gamma\delta}$ respectively, therefore, total released field is $\overline{cd} - \overline{ab} + \overline{\alpha\beta} - \overline{\gamma\delta}$ which equals $-\overline{gf}$. Then the magnitude $-\overline{gf}$ is the initial value of the free decaying field released by the first discharge. The resultant of E′ and the free decaying field is the field recovery curve after the first discharge as represented by E (after 100 sec).

The second discharge occurs at t = 174 sec. At this instant, as in the case of the first discharge, E'_{q+} and E'_{q-} change from a′ to c′ and α' to γ' respectively. Consequently E′ changes from e′ to f′ or E changes from i′ to j′ ($\overline{e'f'} = \overline{i'j'}$). The curves E''_{q+}, E''_+, E''_{q-}, and E''_- shown after the second discharge have the same meaning with E'_{q+}, E'_+, E'_{q-}, and E'_- respectively. The resultant $E''(= E''_+ + E''_-)$ grows starting from g′. Therefore, the magnitude of $-\overline{g'j'}$ is the initial value (at t = 174 sec) of the free decaying field which consists of two parts, the one is released by the second discharge and the other is remainder released by the first discharge. The resultant field of E″ and the free decaying field are represented by E (after 174 sec) showing the field recovery curve after the second discharge.

By similar procedures the field recovery curves after the subsequent discharges will be obtained.

Using this graphical method, recovery curves for various values of r are obtained and shown in Figure 5. In this case it is assumed at t = 0, electric field was absent and at t = 90 sec the first discharge occurred neutralizing 35 coulombs ($= 0.5 \times 80 \times (1 - e^{-4\pi \times 1.8 \times 10^{-3} \times 90})$ coulombs).

Thereafter the discharges repeated with the constant interval of 67 sec. Curves for r = 0 km and r = 20 km are representatives of near and distant storms respectively. Curves for r = 8 and 12 km are examples of storm at intermediate distances. These curves well represent the characteristic features of those in Figure 1 as well as Figure 2.

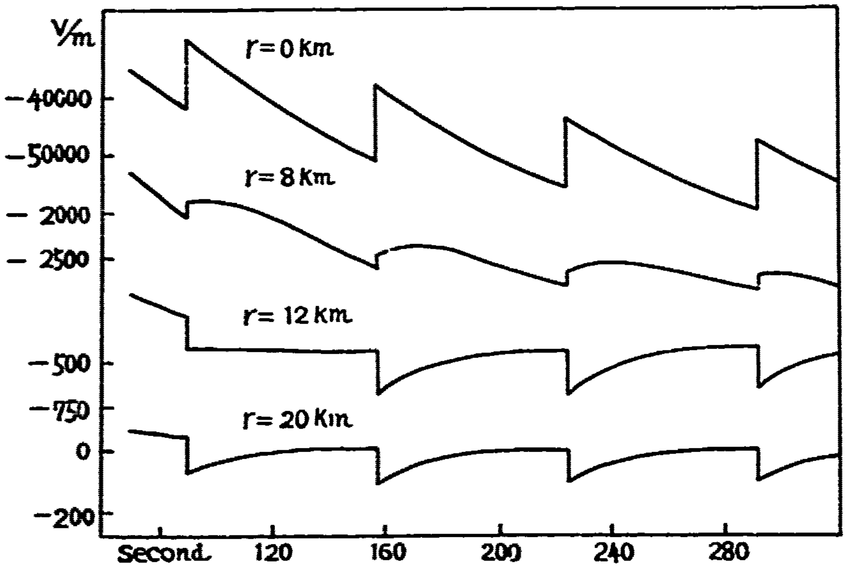


Fig. 5--Field recovery curves at various distances (calculated)

<u>Discussion</u>--Relating to the mathematical analysis and numerical calculations performed in the previous paragraphs, the following remarks will be necessary:

(1) The recovery curves in Figure 5 were obtained assuming that half of total positive charge (and corresponding negative charge) was neutralized. In the case the total positive charge is neutralized, important features of the curves will not alter. Also, it is obvious that the form of the curves does not depend on the magnitude of supply current J_o. On the other hand, the characteristic features will depend on the interval between lightning discharges. For more frequent discharges than assumed in the example, characteristic features of field recovery for a distant storm becomes less marked, namely discharges will occur when the field is in rising state. This matter is also the same in actual storms having very frequent discharges.

(2) It has been assumed the supply current J_o is constant. If this current diminishes owing to the retarding effect of the electric field within cloud, instead of by (1), Q will be expressed by

$$Q = Q_i e^{-\lambda_1 t} + Q_s(1 - e^{-(\lambda_1+\gamma)t}) \quad \ldots\ldots\ldots\ldots \quad (27)$$

where $Q_s = J_o/(\lambda + \gamma)$ and γ is a positive quantity depending on the retardation. This modification, however, does not affect the course of the analysis remembering λ_1 be replaced by $\lambda_1 + \gamma$ except for free decaying term. For example, (22) is replaced by

$$E = E_{qs}(1 - e^{-(\lambda_1+\gamma)t}) + E_{\rho s}\Big\{1 - e^{-(\lambda_1+\gamma)t} + [(\lambda_1 + \gamma)/(\lambda_1 + \gamma - \lambda_o)]$$
$$[e^{-(\lambda_1+\gamma)t} - e^{-\lambda_o t}]\Big\} + E_i e^{-\lambda_o t} \quad \ldots\ldots\ldots\ldots \quad (28)$$

where E_{qs} and $E_{\rho s}$ are $\lambda_1/(\lambda_1 + \gamma)$ times those in (22). Resulting recovery curves will have similar features to those shown in Figure 5.

(3) In case a simple dipole cloud is imbedded in an atmosphere of uniform conductivity, as previously pointed out by WILSON [1921], the following relation will hold

$$\frac{(\partial E/\partial t)_{t=0}}{E} = \frac{J_0}{Q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

where $(\partial E/\partial t)_{t=0}$ is initial rate of field recovery, E is the sudden field change accompanying lightning, J is the supply current in a cloud and Q is the charge destroyed by lightning. Since the left hand side of (29) is measurable, as has been done by WILSON [1921], SCHONLAND [1928] as well as WORMELL [1939], J_0/Q will be estimated by the observations of electric field on the ground.

According to the present analysis, corresponding relation is

$$\frac{(\partial E/\partial t)_{t=0} + \lambda_0 E_i}{E} = \frac{J_0}{Q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

Eq. (29) as well as (30) are obtained assuming initial accumulation of charge is absent. If initial charges are present these relations will become more complicated in form.

Acknowledgments--The writer is indebted to M. Hasegawa in many respects, especially for providing his special type of rotating collector by means of which the electric field of thunderstorms observed and for his continued interest and encouragement in the course of the present study. Many thanks are also due to Z. Hashimoto of Ritsumeikan University and S. Kato for their valuable criticism relating to the mathematical analysis in this work.

References

GISH, O. H., and G. R. WAIT, Thunderstorms and the Earth's general electrification, J. Geophys. Res., v. 55, pp. 473-484, 1950.

GUNN, R., Electricity of rain and thunderstorms, Terr. Mag., v. 40, pp. 79-106, 1935.

HASEGAWA, M., Rapidly acting collectors for the measurement of atmospheric electricity, Chikyu Butsuri, v. 4, pp. 161-169, 1940 (in Japanese).

HOLZER, R. E., and D. S. SAXON, Distribution of electrical conduction currents in the vicinity of thunderstorms, J. Geophys. Res., v. 57, pp. 207-216, 1952.

KASEMIR, H. W., Studien über das atmosphärische Potentialgefalle-IV. Zur Strömungstheorie des luftelektrischen Feldes-1, Arch. Met. Geophys. Biokl., A, v. 3, pp. 84-97, 1950.

SCHONLAND, B. F. J., The polarity of thunderclouds, Proc. R. Soc., A, v. 118, pp. 233-251, 1928.

SIMPSON, G. C., The mechanism of thunderstorms, Proc. R. Soc., A, v. 114, pp. 376-401, 1927.

TAMURA, Y., On the distribution of electricity in thunderclouds, J. Geomag. Geoelect., v. 1, pp. 22-25, 1949.

WILSON, C. T. R., Investigations on lightning discharges and on the electric field of thunderstorms, Phil. Trans. A, v. 221, pp. 73-115, 1921.

WORMELL, T. W., The effects of thunderstorms and lightning discharges on the Earth's electric field, Phil. Trans., A, v. 238, pp. 249-303, 1939.

MAGNETIC-FIELD VARIATIONS IN THE VICINITY OF LIGHTNING

Harald Norinder

Institute of High Tension Research
University of Uppsala, Uppsala, Sweden

The investigation of the electromagnetic field variation in lightning strokes involves a problem of considerable experimental difficulty. Two essentially different methods for such an investigation exist (a) the linear open antenna method [NORINDER, 1952], and (b) the closed antenna or frame aerial method [NORINDER and DAHLE, 1945]. The variations using cathode ray oscillographs in combination with an antenna system and aperiodic amplifiers are analyzed in both methods. When an analysis is required to show details of the electromagnetic variation features of the lightning, the open antenna method has drawbacks.

My intention here will be to give an account of unpublished results of the variations of the magnetic field recently obtained by the frame aerial method. The measurements were carried out during the thunderstorm season of 1953 at the Institute of High Tension Research, University of Uppsala. In the investigation, two frame aerials have been used, the plane of one was perpendicular to and the plane of the other was parallel to the Earth's surface. Hence it was possible to analyze both horizontal and vertical magnetic-field components. The vertical field components are the chief interest of this paper.

The investigations have been carried out by using two separate field stations, one, Husbyborg, situated at the Institute and the other, Funbo, at a distance of 12 km. One of the two measuring stations used during the trials is shown in Figure 1. The oscillographic equipment of one of the stations is shown in Figure 2.

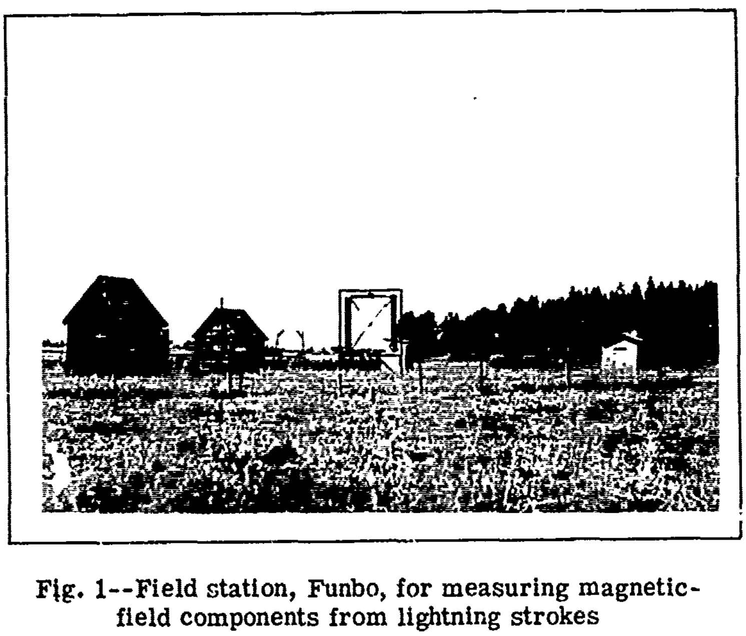


Fig. 1--Field station, Funbo, for measuring magnetic-field components from lightning strokes

The signals have been recorded by applying two different linear time bases with sweep times of 100 μsec or 5000 μsec respectively. The main part of the lightning strokes was recorded with the longer sweep time.

Before passing to a detailed treatment of the results I am forced to make some remarks with regard to the configurations of the lightning path. We must not forget that regular forms are exceptions. Some photographs taken by the French author, Sourdillon [1953], who has used a method to photograph lightning paths in full daylight, will support this opinion (see Fig. 3). As can be observed by the photograph the lightning paths are indeed very complicated. If we are operating simultaneously with frame aerials in vertical and in horizontal planes, we will thus obtain very characteristic components on both systems.

During the thunderstorm season of 1953 about 5000 oscillograms were obtained within a distance of 20 km from lightning discharges. A little more than half were too complicated to permit an analysis. Our treatment has been limited to about 2300 lightning strokes.

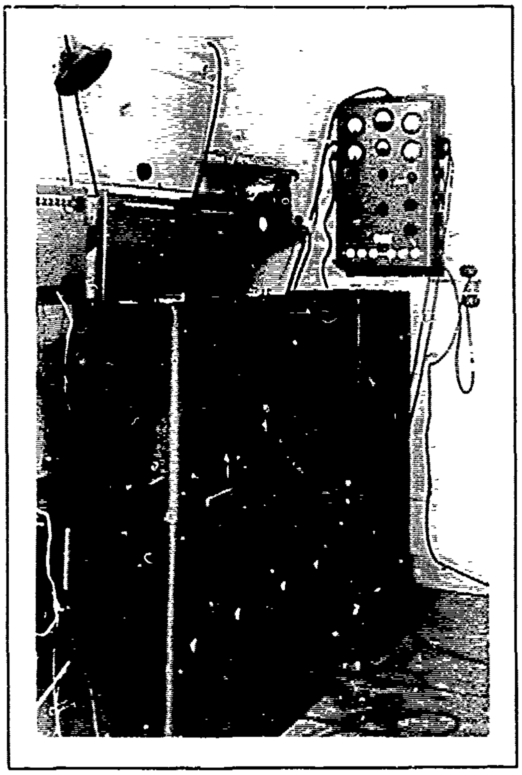


Fig. 2--Cathode ray oscillographic equipment used for investigations

Some originals of the recorded oscillograms are reproduced in Figures 4 and 5. Evidently the variation phenomena that we have to analyze are very complicated and it is always necessary to be very careful when analyzing the curves.

The data gathered show such variation in form of lightning discharge that there is difficulty in presenting them.

A survey of the distribution of polarities is shown in Table 1. We observe a very marked predominance (about 90 pct of the field force values) with negative amplitude, indicating currents from negative-charge concentrations. This is in full agreement to what has resulted from our earlier investigations [NORINDER and DAHLE, 1945]. The unipolar positive values are observed in three pct of the cases while discharges showing the same order of magnitude for both polarities occur in five to seven pct of the cases.

The thunderstorm cloud considered as a machine generating multiple strokes with a pronounced regularity follows from a glance at the sequences of multiple strokes passing in the same lightning channel. This is exemplified by Figure 6.

Of interest are the field amplitudes of the predischarges as compared with the ones following the main and partial discharges. The relations are in general varying between a few per cent and in exceptional cases up to 20 pct.

Variation of the magnetic field characterized by a double polarity where the variation in amplitudes attain values of about the same order of magnitude are rather scarce.

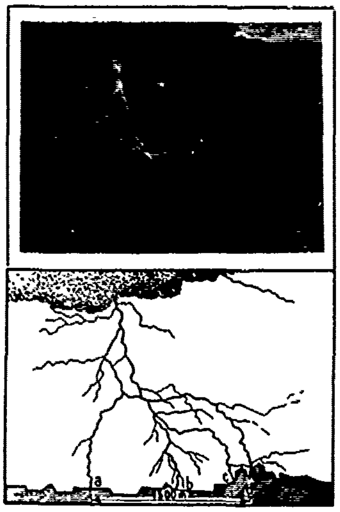


Fig. 3--Photographs of lightning strokes in full daylight taken by Sourdillon showing complexity of discharge procedure

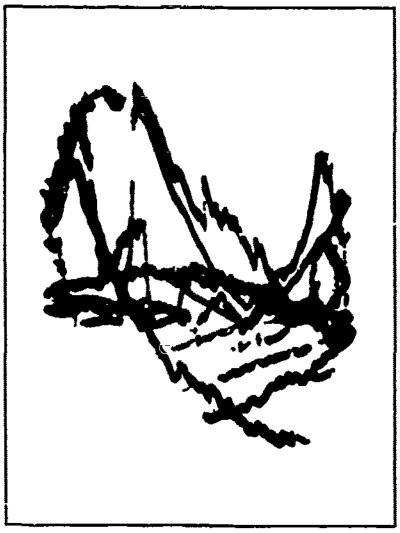


Fig. 4--Original of recorded oscillograms used in investigations

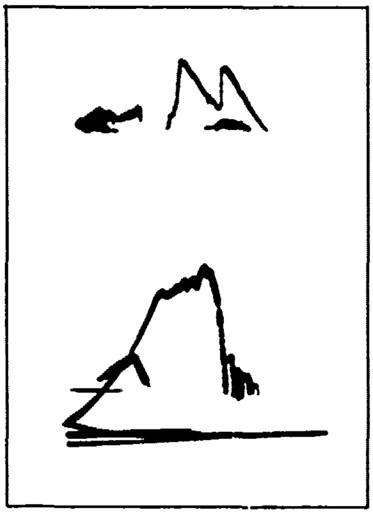


Fig. 5--Original of recorded oscillograms used in investigations

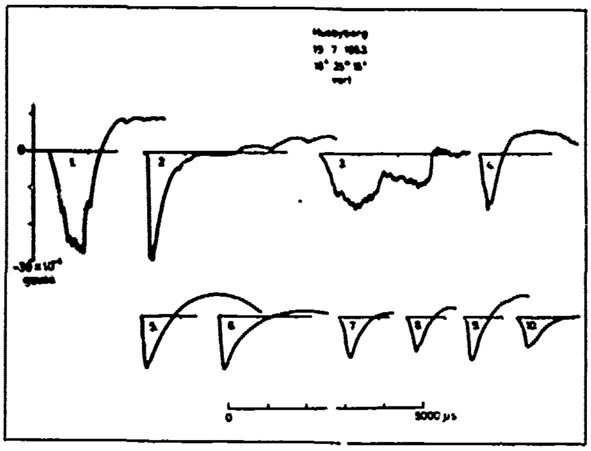


Fig. 6--Recorded multiple strokes in the same lightning path

A close examination of all available magnetic-variation forms render the immediate impression that they are characterized by rapid superimposed variations either occurring only at the fore parts of the curves or extending along short or long parts of the variation curve. Nevertheless there exist typical exceptions from the form mentioned where the recorded magnetic-field variation shows a quite distinctive lack of any rapid variation. This type must be caused by an integral effect originating from a lot of streamers between volumes with opposite polarities. The discharge has sometimes the feature of a glow discharge, and sometimes consisting only of repeated predischarges. Personally, during heavy night thunderstorms in mountainous regions in Switzerland, I have observed very extended volumes with the typical feature of a glow discharge process. A second justification that we have to deal with glow discharges is based on the very slow sloping fronts that are characteristic of the variation type mentioned.

Table 1--Distribution of polarity

Stations: Husbyborg and Funbo 1953; vertical frame; time base: 5000 μsec

Item	Total number	Negative	Positive	Double polarity
		pct	pct	pct
First discharge	934	90	3	7
Following partial discharges	1352	92	3	5
Total and averages	2286	91.5	2.9	5.6

A general survey of the variation types of the magnetic field results very often in curves with superimposed and typical rapid variations. The successive steps have considerably varying amplitudes and the time intervals between them also vary.

The superimposed rapid variations can in other discharges be spread out over the whole curve with a characteristic stepwise starting development on the frontal part or over the whole of the curve. Rapid variations are seldom located on the back parts of the curves. Sometimes a very strange form of the magnetic variation curves has been obtained with jagged and great variations extended over the main part of the curve.

In general the variation forms of the magnetic field are more changing than would be expected.

The analysis carried out of the distribution of the number of multiple strokes show that the most frequent numbers in the same path are two and three. As many as 17 have been observed.

The use of a long time base of 5000 μsec allowed measurements of discharges of an obviously long duration with their half time values attaining up to 4000 μsec (see Fig. 7). Evidently many of these discharges must be caused as an integral effect from a number of currents consisting of very weak glow discharges between ionized volumes inside thunderstorm clouds.

An analysis has been carried out in order to estimate the percentage of the total discharge time which has been covered by the superimposed rapid variations. The most frequent period covered a time below 20 pct of the total duration of the curve.

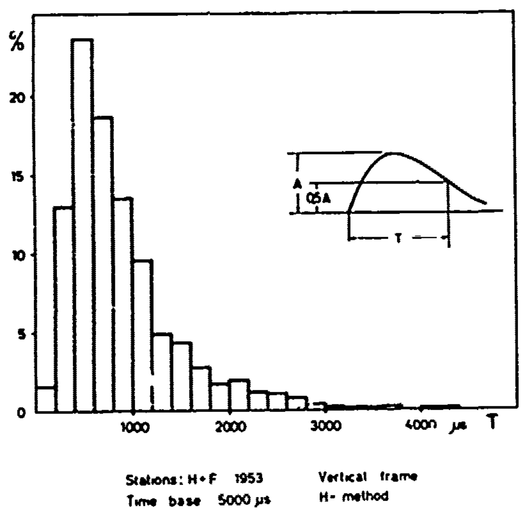


Fig. 7--Distribution of half-time values of duration

The superimposed rapid variations are interesting from a special point of view. In the International Union of Scientific Radio (URSI) General Assembly a wave-length of about 11 km was recommended as the most suitable one for tuned direction finders adapted for locating distant thunderstorm centers. This wave-length was determined experimentally. The author has stated [NORINDER, 1952] in an investigation of the electric field components from lightning strokes that quasi-periodic wave-lengths of the values mentioned occur as superimposed both in predischarges and in the main and partial discharges of lightning strokes (see Fig. 8). Hence it is of a special interest to find out if such quasi-periodic superimposed rapid variations of wave-lengths of the order mentioned also can be discovered in the variation curves from the magnetic field. A test has been carried out dealing with the superimposed variations on the fore or frontal parts of the magnetic curves. It showed (see Fig. 9) that the quasi-periodic wave-lengths which occur frequently, are located between 7.5 and 20 km.

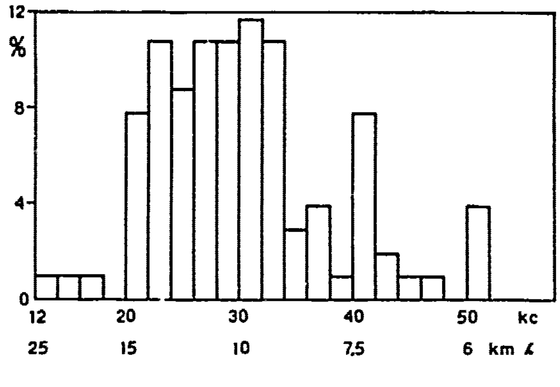


Fig. 8--Quasi-periodic wave lengths as measured by method of electric field variations

The records obtained with the short time base of 100 μ sec permit the analysis of shorter superimposed quasi-periodic variations. Curves from the vertical-frame aerials have been used and show an accumulation of wave lengths of 300 to 600 m.

The time during which the lightning current will reach its peak value has always appeared as an interesting problem. In the first place we will consider the results using the time base of 5000 μ sec. In this case we will obviously be able to observe frontal rise time values of a very considerable length. The distribution of fronts show, in fact, that the main part of the frontal times do not exceed 200 μ sec. But values somewhat longer than 1000 μ sec have also been observed. Evidently we have to deal with slow moving discharges of a glowing type between charged volumes without a development of sparks in the usual sense. Sometimes the long durations of the frontal times may be caused by very long lightning sparks.

The slow moving time base variation did not allow an analysis of the rapid frontal variations which are of special interest from many points of view, especially as they cover the fronts of the shortest lightning sparks or discharges between charges of opposite sign. This circumstance has caused us to investigate the frontal values by using available oscillograms from both vertical and horizontal frames operating at a time base of 100 μ sec. Both the H and dH/dt method have been used in this analysis.

The result is extremely interesting. The values taken on horizontal frames showed very short frontal values with the most frequently occurring being two or three μ sec respectively. The most frequent values as calculated from the vertical components are from six to nine μsec (see Fig. 10). The dH/dt method agrees very well with the H method. The values are in very good agreement with what has earlier been obtained [NORINDER and DAHLE, 1945] when vertical lightning strokes were measured. It seems to be too early to present a correct physical explanation of why the horizontal components are characterized by much shorter frontal values. The most plausible explanation appears to be that the horizontal components in many cases are caused by short discharge paths as compared with the discharges that are causing vertical magnetic-field components. In this consideration the very long horizontal lightning paths are excluded. Their long duration requires another measuring technique.

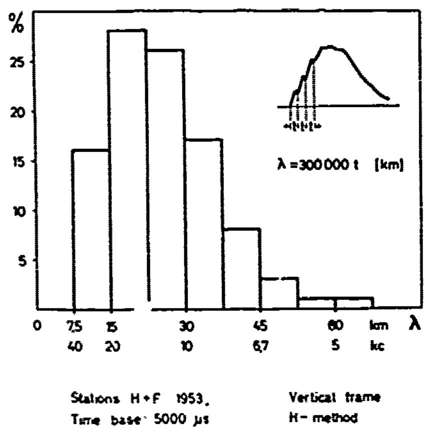


Fig. 9--Quasi-periodic wave lengths located in the frontal parts of discharge magnetic curves

A statistical study has been made of the frequency of the occurrence of vertical components of the maximal magnetic field where the values are collected from recorded discharges within the sensitivity region mentioned before of up to 19 km from the stations. The most frequent values are

found below 50×10^{-4} gauss. Values as high as $200 - 300 \times 10^{-4}$ gauss have also been measured (see Fig. 11).

The ratio of the field force observed simultaneously on the vertical and horizontal frame aerials has been computed. The ratio is given for different distances in Table 2. The horizontal frame records about 30 pct of the field force taken simultaneously on a vertical frame.

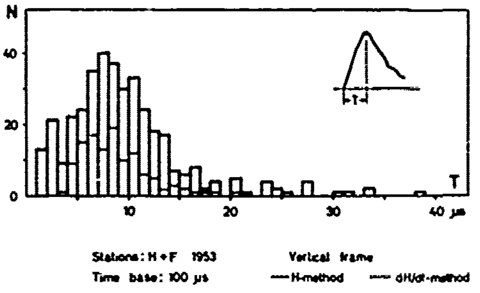


Fig. 10--Analysis of frontal values by rapid time axis of 100 μsec obtained by vertical frame; both H and dH/dt methods were used

Table 2--Comparison between field force values from vertical and horizontal frame aerials

Station: Husbyborg; H method; time base 100 μsec; 1953

Lightning distance	Amplitude ratio: Horizontal frame/vertical frame
km	pct
0-3	27.6
3-6	36.5
6-9	22.5
9-12	20.8

The distances between the lightning strokes and the observation stations could be obtained for a number of cases. These distances have been plotted against the recorded variations of the vertical magnetic field. It is well known from earlier investigations that the peak values of currents in lightning strokes vary within wide limits [NORINDER and DAHLE, 1945]. From this it must be anticipated that the variation of peak values of the magnetic field with distance will show considerable scatter (see Fig. 12). A marked decrease tendency of the amplitudes is visible at distances greater than six kilometers. The maximum value attained during the observation period was 250×10^{-4} gauss.

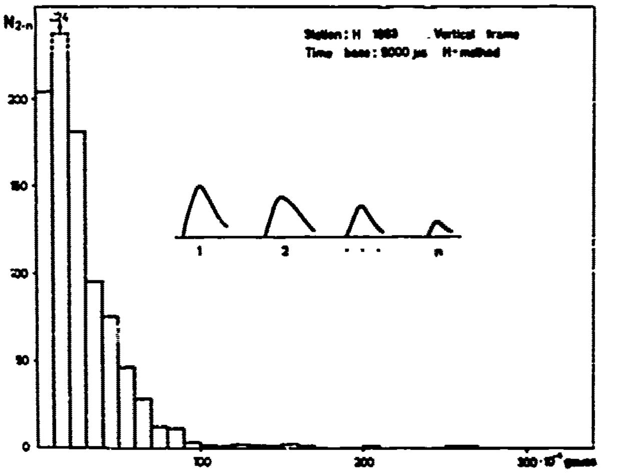


Fig. 11--Maximum magnetic-field variations recorded by vertical-frame aerial within sensitivity range of 19 km from antenna

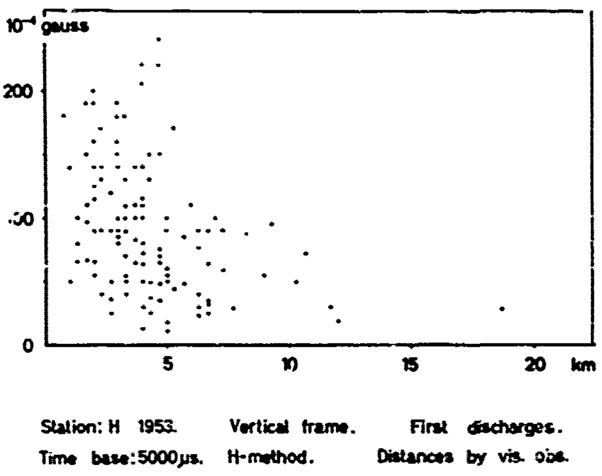


Fig. 12--Scatter diagram of distance versus magnetic field force using vertical-frame aerial

Of greatest interest is an analysis of the magnetic-field variations taken simultaneously from the same lightning discharge on two stations. In this we have used in our preliminary investigation the stations at Husbyborg and Funbo. More extensive measurements of this problem are under

preparation. Some examples of the results thus far obtained (see Fig. 13) show a very good agreement. In an investigation that we are preparing, an analysis of records will be undertaken where the distances between the stations used will be diminished to about the half of that mentioned.

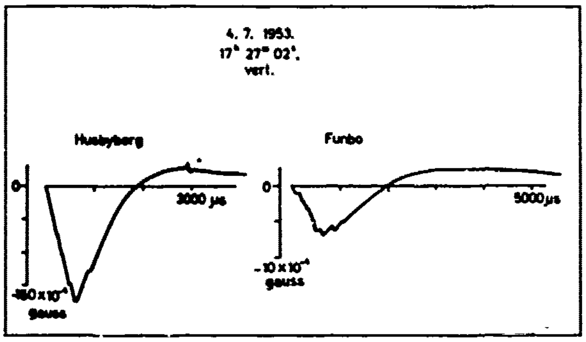


Fig. 13--Magnetic-field variations from the same lightning discharge recorded simultaneously at two stations 12 km apart

A more extensive account of these investigations will be published in Arkiv for Geofysik, Kungl. Svenska Vetenskapsakademien, Stockholm.

Summary--An investigation has been carried out to analyze the variations in the magnetic field produced by lightning discharges. The frame-aerial method introduced by the author was used. Both horizontal and vertical frame aerials were used to record the respective components of the variations in the magnetic field. The measurements were undertaken at two stations 12 km apart. Both stations were equipped with specially constructed recording cathode ray oscillographs combined with amplifiers. By an integrating circuit in the units the oscillographs recorded directly the variation curves H of the magnetic field. In some cases another recording method was introduced by which the first derivative dH/dt of the magnetic field was obtained directly.

Within the measuring distances of up to 19 km from the lightning paths the investigation yielded values of the magnetic field up to 200 - 300 $\times 10^{-4}$ gauss.

An analysis of the variation in the magnetic field was carried out either by using a rapid time variation axis of 100 μsec or a slow moving one of 5000 μsec, an arrangement which permitted the measurement not only of rapid time variations but also of extremely slow ones. The latter were evidently caused by glow discharges between volume charges of opposite sign within the thunderstorm clouds. The rapid variations were related to shorter or longer sparks in the lightning paths.

Simultaneous measurements of the magnetic-field variations produced by lightning discharges with frame aerials in vertical and horizontal planes indicated that the amplitudes of the vertical components of the magnetic field attained, on an average, only 30 pct of the horizontal components.

Simultaneous records of the same lightning discharges at the two stations situated 12 km apart showed very good agreement.

References

NORINDER, H., Variations of the electric field in the vicinity of lightning discharges, Arkiv för Geofys., v. 1, no. 20, p. 543, 1952.

NORINDER, H., and O. DAHLE, Measurements by frame aerials of current variations in lightning discharges, Arkiv för Mat., Astron. Fysik, v. 32A, no. 5, p. 1, 1945.

SOURDILLON, M., Note sur les 'Familles d'Éclairs,' La Météorologie, Paris, Jan.-Mar. 1953.

EXPERIMENTAL STUDY OF ELECTRIFICATION OF SNOW

Harald Norinder and Reinhards Siksna

Institute for High Tension Research
University of Uppsala, Uppsala, Sweden

Introduction--Electrification of snow is a phenomenon that has been known for a long time, but the results obtained by the many investigators of it have frequently been contradictory. The problem has recently been taken up for renewed consideration. There are two particular fields where knowledge about the electrification of snow may be of importance. The first of them concerns the so-called precipitation static, that is, the electrical disturbances interfering with telecommunications when an aeroplane flies through a snow cloud. Some of the results of such investigations are to be found in publications of the U. S. Army-Navy Precipitation Static Project [U. S. ARMY-NAVY PRECIPITATION-STATIC PROJECT, 1946]. Since practical considerations were paramount in this project, the general problems associated with the electrification of snow were of secondary significance; but the report nevertheless contains results of a fairly general importance. A more universal treatment of the phenomenon in question is given in another report on precipitation static, from research carried out on behalf of the U. S. Army Air Forces [SCHAEFER, 1948].

Another field, in which it is of importance to know the phenomena of electrification of snow, is that relating to the production of electrical charges during thunderstorm conditions. CHALMERS [1953] states that he has succeeded in extending the results of an investigation of electrification of snow by friction carried out by PEARCE and CURRIE [1949]. He says that, as a result, he has succeeded in confirming the ice-friction theory of SIMPSON and SCRASE [1937] which was developed to explain the production of the thunderstorm electricity.

It might seem that the problems associated with electrification of snow approach a status of definite classification as a result of these recent investigations; but this is not the case. For one thing, if the electrification of snow is investigated with a view to applying the results obtained to the explanation of other phenomena, or for confirmation of a given theory, the problem will be considered one-sidedly. And, secondly, experimental investigations with snow are not so simple as they might seem to be, owing to various properties, mostly unknown, of the thing investigated--the snow itself.

A critical examination of the theories of charge generation in thunderstorms has recently been given by MASON [1953] who states that 'during the last forty years, at least eight different mechanisms for the generation of electricity in thunderclouds have achieved prominence in the literature. Too often theories have been formulated without sufficient regard to all the available experimental data on the behaviour of thunderstorms.' It could be added that our knowledge of the experimental data concerning electrification of the subjects related to the problem is not complete either, as will be shown below.

One of the authors [NORINDER, 1949] has discussed the possibilities of the genesis of a special type of atmospherics produced within snow squalls. The ideas considered in that discussion have largely inspired the present investigation, but some additional points of view of a more general nature were also taken into consideration.

The electrification of snow and related phenomena were investigated by measuring: (1) the charge of snow when it is poured from a vessel into a funnel; (2) the charging of an insulated target onto which snow was blown and the charge of the scattered snow; and (3) the charge in air due to blowing snow.

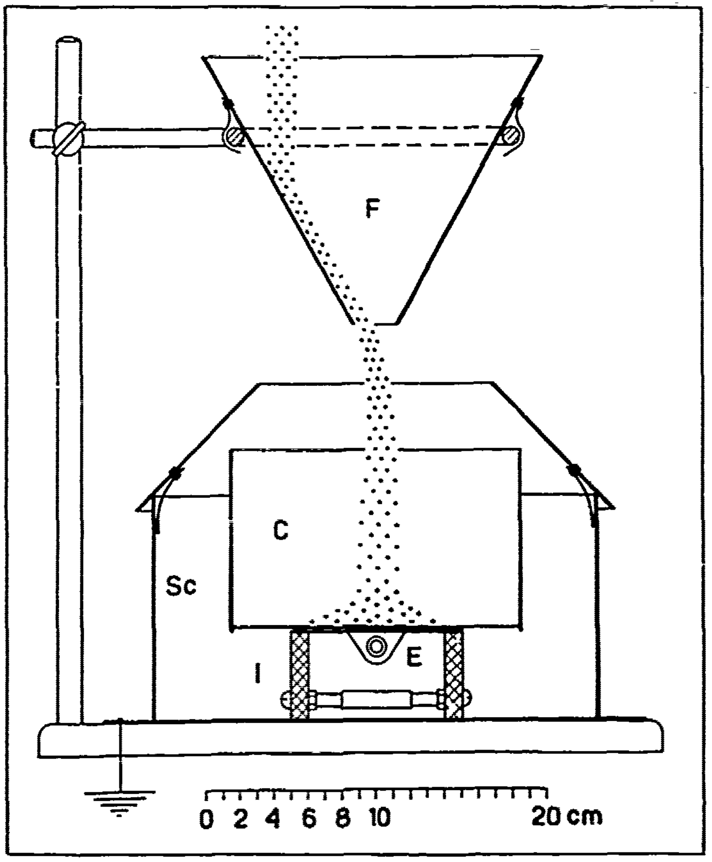


Fig. 1--Device for pouring-snow experiments: F, funnel; C, collector; Sc, screening vessel; E, connector for cable to electrometer

Some experiments concerning electrification of snow

A detailed account of this part of the investigation will be found in papers by NORINDER and SIKSNA [1953b; 1954].

The electric charge on snow falling on a funnel--The device used is shown in Figure 1. Snow was poured from a vessel into the funnel F. A cylindrical collector C was placed on the polystyrene insulators I in the screening vessel Sc. The collector was connected with the Wulf bifilar electrometer. The following vessels and funnels were used: metallic, paper-coated, and paper-coated, impregnated first with water, frozen, and thereafter covered with ice by repeated immersion in water and freezing.

Under the same conditions, snow was charged negatively when falling on metallic or ice surface, and positively when falling on a paper surface (Table 1, Jan. 26 and 30, and Feb. 9), although under other conditions it was negatively charged when falling on a paper surface (Feb. 1). The same snow thus received charges of a different sign depending upon the surface onto which it impinged. The properties of the 'other partner' defined the charge, and also the polarity, of falling snow. The magnitude of the effect was further dependent on the structure of snow and on the temperature. At a lower temperature the effect was larger.

Table 1--Electric charge in 10^{-10} coulombs per gram of snow poured into funnel

Date	Weather	Temperature	Snow density	Funnel Metal	Funnel Ice	Funnel Paper
1953		°C				
Jan. 26	...	- 4	0.5	(-) 0.38	(-)0.35	(+)0.37
	...			...	(-)0.29	...
Jan. 30	...	- 1	0.24	(-) 0.7	(-)0.3	(+)1.3
Feb. 3	...	- 7	0.22	(-) 0.96	...	...
		- 4	drifted	(-) 1.00	...	...
Feb. 5	strong wind	- 8	0.25	(-)18.4	(-)1.0	a
				(-) 8.6	...	...
				(-)15.2	...	...
Feb. 6	...	-12	0.29	(-)35.4	(-)0.88	a
				(-)38	(-)0.95	
				(-)39.4	(-)0.45	
					(-)0.42	
					(-)0.93	
					(-)1.19	
					(-)0.96	
Feb. 7	wind	-16	0.3 old granu-lated	(-)21.0	(-)0.72	(-)1.56
				(-)23.0	(-)0.55	(-)1.36
				(-)22.0	...	(-)1.35
				(-)19.0	...	(-)1.44
				...	...	(-)2.24
				...	...	(-)2.40
			0.17 fresh soft	(-)29.0	(-)1.25	(-)0.20
				(-)26.6	(-)0.53	(-)0.12
Feb. 9	windless, snow falling	- 9.6	0.47 old granu-lated	(-) 1.35	...	a
		- 8		(-) 1.05	...	
				(-) 1.15	...	
				(-) 1.10	(-)0.39	a
				(-) 0.47	(-)0.15	
				(-) 0.94	(-)0.26	
			0.09 fresh	(-) 8.7	(-)1.45	(-)1.7
				(-) 7.1	(-)0.93	(-)1.5
				(-) 7.6	...	Funnel heated up
				...	...	(+)0.67
				...	...	(+)0.58
				...	...	(+)0.45
				...	...	(+)0.60

[a]Indefinite, collector discharged independent on the polarity of the charge at the beginning.

Table 2--Charge on insulated plates of various materials when hit by blowing snow

Date	Temperature	Plate	Charge in 10^{-10} coulombs, per gram of snow		
			Plat[illegible] beginning		
			(+) charged	[illegible]) charged	un-charged
1953	°C				
Feb. 13	-10	Aluminium	(+) 6.2	[illegible]	...
			(+) 8.5	[illegible]	...
			(+) 5.8	(+) 7.2	...
Feb. 14	- 5		...	...	(+)12.2
			...	...	(+)13.0
Feb. 13	-10	Pasteboard	(-)40.0	(-)21.7	...
			(-)37.4	(-)23.0	...
			(-)36.1	(-)24.4	...
Feb. 14	- 7	Pasteboard	...	...	(-)22.8
			...	...	(-)25.0
			...	...	(-)29.6
			...	...	(-)25.6
Feb. 13	-10	Pasteboard covered with ice	(+)10.0	(+)18.6	(+)10.2
			(+) 6.3	(+)13.0	(+)11.8
			(+) 6.3	(+)11.7	(+)14.9
			(+) 8.5	...	...
Feb. 14	- 7	Wood	...	...	(-)13.6
			...	...	(-)12.4
			...	...	(-)12.2
			...	...	(-)14.6
Feb. 14	- 6	Bakelite	...	...	(-)11.9
			...	...	(-)11.8
			...	...	(-)11.2
			...	...	(-)16.8
Feb. 14	- 6	Plexiglas	...	...	(+) 9.0
			...	...	(+) 6.3
			...	...	(+) 7.1
			...	...	(+) 6.7

The electrical charging of an insulated plate when blowing snow--A device for snow blast was built as shown in Figure 2. Snow was poured into a metallic funnel F connected with a flexible tube T. Air was blown into the tube by an electrically driven blower B. The device was suitable for obtaining a jet of snow which could be blasted against different targets, for instance, against an insulated plate. The plate was charged up to a comparatively high potential even when using smaller quantities of snow. Short sparks were occasionally obtained from the plate. The charging of the plate was measured by a Wulf electrometer E (Fig. 2 (I)). The charge of the large snow particles scattered was measured in the collector C (Fig. 2 (II)). The charge varied depending upon whether the plate was insulated or grounded (Fig. 2 (III)).

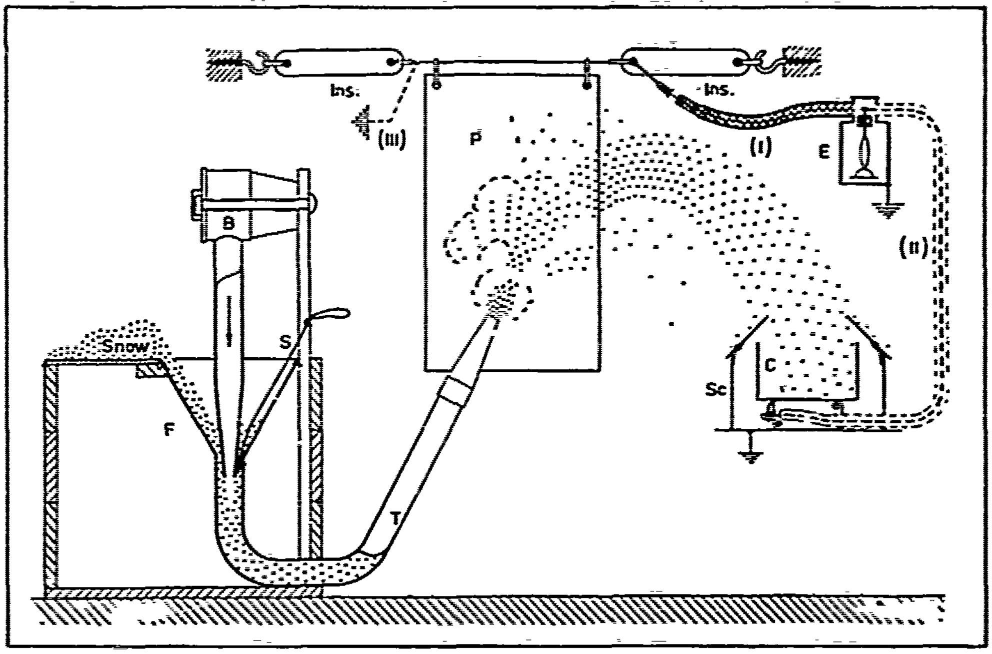


Fig. 2--Arrangement for experiments by blowing snow: B, air blower; F, funnel; S, stirrer; P, plate of various materials; Ins, polystyrene insulators; E, electrometer; C, collector; Sc, screening vessel

A marked charging effect was produced when blowing a snow jet against different targets: metal and pasteboard covered with ice were positively charged, and pasteboard, wood, bakelite were negatively charged, but a still better insulator such as plexiglas was charged positively (Tables 2 and 3). The charge obtained on pasteboard and wood was extremely large. On the other hand, the charge of a metal plate was highly dependent on the quality of the surface. A greasy iron plate obtained greatly varying charges. A snow block obtained an enormous positive charge. At a lower temperature the effect was larger also in these cases.

The importance of the surface--The experiments considered would seem to show conclusively the importance of the properties of the 'touching' surfaces. This is even more pronounced, as shown by experiments at temperatures near zero, when dry pasteboard and wooden plates were negatively charged, while the charge changed into positive when the plates were moistened. A similar, though somewhat less pronounced, effect was also observed on metal surfaces.

Charge of large snow particles scattered from the plate--One fact seems to contradict the conception considered, namely, that the large snow particles scattered from the target when struck by a stream of snow were in all cases positively charged, irrespective of whether the target charged by snow was charged positively (metallic surface, ice block) or negatively (pasteboard, wood) (see Table 3). In addition it must be pointed out here that the large snow particles were negatively charged only in one case--when scattered from a grounded snow block. The charge of the scattered large snow particles per gram of snow was generally larger than that obtained on the target per gram of snow. But until now, the third possible 'partner' of the effect, the air (or the very small snow particles in the air), has not been considered.

Electrical charges measured in the air while blowing snow
(Presented here for the first time)

Measuring the charges in the air--It was evident that in the presence of blowing snow, particles of small dimensions could be expected to be present also in the air and it was not possible to collect

Table 3--Charge in 10^{-10} coulombs per gram of snow[a] of an insulated plate when hit by blowing snow, and charge on larger snow particles blown away from the plate and collected in a collector, when the plate was insulated and when grounded

Date	Temperature	Plate	Charge of insulated plate	Charge carried by larger snow particles — Plate — Insulated	Charge carried by larger snow particles — Plate — Grounded
1953	°C				
Feb. 20	-2.5	Aluminium	...	(+) 60[b]	(+) 60[b]
			...	(+) 48[b]	...
		Pasteboard	...	(+)130[b]	(+)190[b]
			...	(+)115[b]	...
	-1.5	Snow block	(+)44[b]	(+)145[b]	(-) 25[b]
			(+)55[b]	(+)185[b]	(-) 36[b]
Feb. 24	-2	Iron very carefully cleaned	(+) 1.1	(+) 3.8	(+) 1.15
			(+) 1.0	(+) 3.0	(+) 4.7
			(+) 2.3	...	...
	-1.5	Pasteboard	(-) 5.2	(+) 10.5	(+) 27
			(-) 4.4	(+) 8.2	(+) 33.5
	-1	Wood	(-)10.2	...	...
			(-)12.2	...	...
March 4	-1.5	Wood	(-) 4.7	(+) 85	(+) 83
			...	(+)106	(+) 75
			...	(+) 72	...
	+1	Snow block	(+) 0.82	...	...
			(+) 0.35	...	...
March 5	-1.5	Snow block[c]	(+) 5.5	(+) 3.2	(+) 1.6
			(+) 7.0	(+) 1.9	(+) 1.8

[a]Except as noted
[b]Total charge in 10^{-10} coulombs of unknown quantity of snow
[c]Coarse-grained snow; snow block very dense

these suspended particles in the collector used. The charge carried by the small snow particles mentioned, and possibly also by the air itself if ionized, may be measured as the net charge, as done by others [PEARCE and CURRIE, 1949; STÄGER, 1925ab], but it would be advantageous if the charges could be separated. The separation was attempted by measuring the charge in the air with ion counters by which ions could also be measured if produced by the snow blast. The ion counters were those used at the Institute for measuring ions in the atmospheric air: an ion counter for small ions equipped with a Weger condenser [SIKSNA, 1953] and an Israël large-ion counter [SIKSNA, 1952a]. For the preliminary measurements the snow blast was arranged in a gap between the observation cabin, where the counters were placed, and a wagon beside it (Fig. 3). Thus, the space where snow was blown was partially screened from winds; however, a little draught caused difficulties in obtaining an even 'snow atmosphere.' For the following series of measurements, therefore, an arrangement shown in Figure 4 was used: the snow jet was blown into a test-room of 6.35 m^3 volume and the air was sucked from this room into the above-mentioned ion counters placed in an adjoining room. It was not possible to obtain an even snow jet during a long period of time with

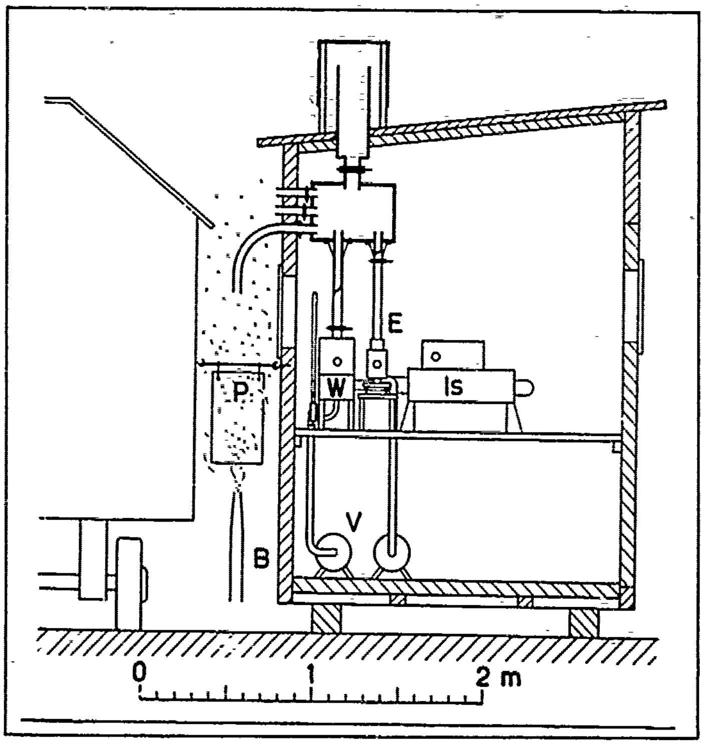


Fig. 3--First arrangement for measuring the charges in the air with ion counters when blowing snow: B, pipe of the snow blower; P, plate; W, small-ion counter with Weger condenser; E, Ebert counter; Is, Israël large-ion counter; V, vacuum cleaners

the blower used, because snow is a material unsuitable for such manipulation. However, no protracted operation was necessary because the electrical state obtained in the test-room when a portion of snow was blasted remained there for some time; indeed, it was transformed with time, but the process of measuring was expected to separate the components of the whole phenomenon. The measurements with the ion counters proved that charges of both polarities were present simultaneously in the air when blowing snow (Fig. 5). Sometimes the positive charge was predominant, sometimes the negative.

Interpretation of the results of measuring with the ion counters--As shown in Figure 5, the shape of the charge-time curves obtained was similar to that obtained when measuring corresponding ions. When charges are measured with an ion counter for small or large ions they can be attributed with certainty as belonging to corresponding ions only if and when it can be assumed that each ion has one elementary charge. This is not always true. In such cases an examination can be performed by considering whether corresponding ions could be present in the air under the given conditions.

Charges measured with the small-ion counter when the controlling electrode is grounded--Charges were also established by the small-ion counter when the controlling electrode of the condenser was grounded (no electric field in the condenser), and the needle of the electrometer moved by leaps. The collecting electrode of the condenser may be charged under these conditions when the concentration of ions of one sign is considerably greater than that of the opposite sign [SIKSNA and METNIEKS, 1953]. This was not the case here. The charging observed and the moving of the electrometer needle by leaps might be explained by assuming that the effect was due to the impact of very small snow particles carrying comparatively high charge on the collecting electrode. Two causes prevented definite measurement of the observed leaps with the apparatus used: (1) the leaps followed too quickly one after another, and (2) their magnitude was not great. The maximum leap

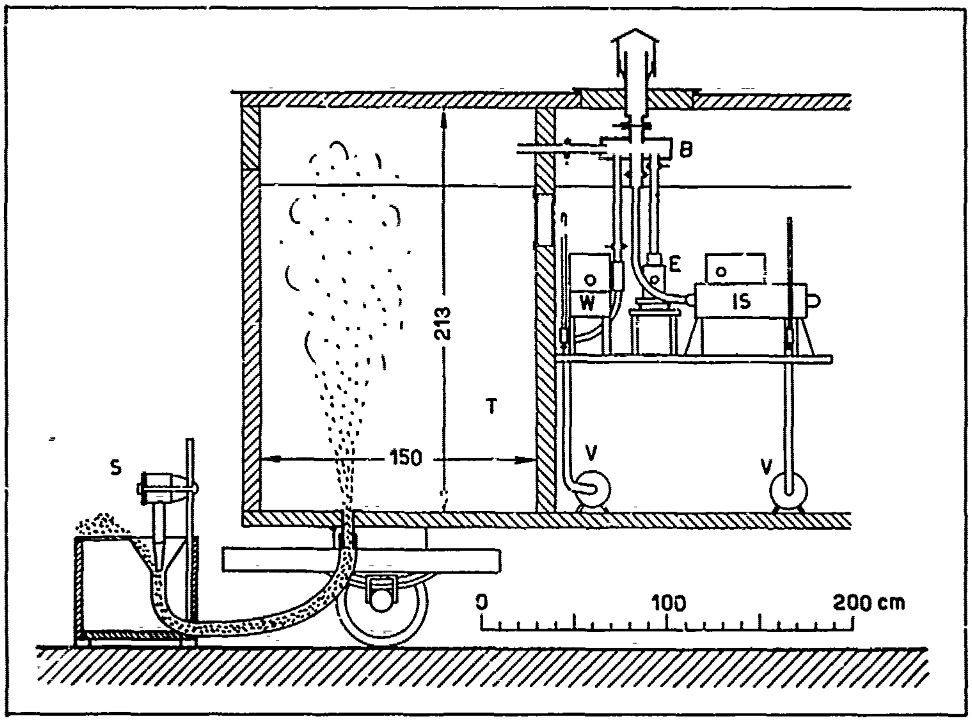


Fig. 4--Second arrangement for measuring the charges in the air with ion counters when blowing snow: S, snow blower; T, test-room; B, suction box; W, small-ion counter with Weger condenser; E, Ebert counter; Is, Israël large-ion counter; V, vacuum cleaners

estimated may be attributed to charge of approximately 700,000 e, yet smaller leaps were frequently observed. A detailed investigation of the effect mentioned would be possible by using a more sensitive apparatus suitable for speedy recording of the charging. However, it can already be noted here that small snow particles with higher charge were collected with the small-ion counter from the air while blowing snow. These particles were mostly charged positively. As an illustration of the phenomenon observed a schematic reconstruction of the event is shown in Figure 6. A definite curve may be obtained for negative charging at controlling potential $U_c = -34$ volts, the negative charge being possibly due to negative ions; at $U_c = -106$ volts the charging is greater, but at $U_c = 0$ (the controlling electrode grounded) the charging is positive and is shown by leaps. The following conclusion may be drawn from the observations: Small snow particles with larger, mostly positive charge were present in the air while blowing snow, and these particles were indicated by the small-ion counter.

Presence of atmospheric small ions in the air when electrifying snow--As shown in the first part of this paper and in the preceding paragraph, electrified particles of snow may be obtained in the air when blowing snow. However, it is not clear how a snow particle may be electrified in the cases mentioned. It might be electrified (1) by friction with other snow particles, (2) by air friction, and (3) by fragmentation. We have no evidence how great a part may be due to each of these processes. Nor can we explain how ions might be formed in the air by the processes (1) and (3). It is hard to believe that considerable numbers of ions could be split from a snow particle by fragmentation. For the time being, the question of how a snow particle may be electrified must be left open. Here, we shall assume only that charged snow particles can be obtained in the air when blowing snow. As has been shown, the charge of a small snow particle can be comparatively large. If a charge of $q = 700{,}000\ e \simeq 3.5 \times 10^{-4}$ esu were placed on a spherical snow particle of a diameter $2\ r = 34\ \mu$, the field on the surface may be

$$E = q/r^2 = 30{,}000\ \text{v/cm}$$

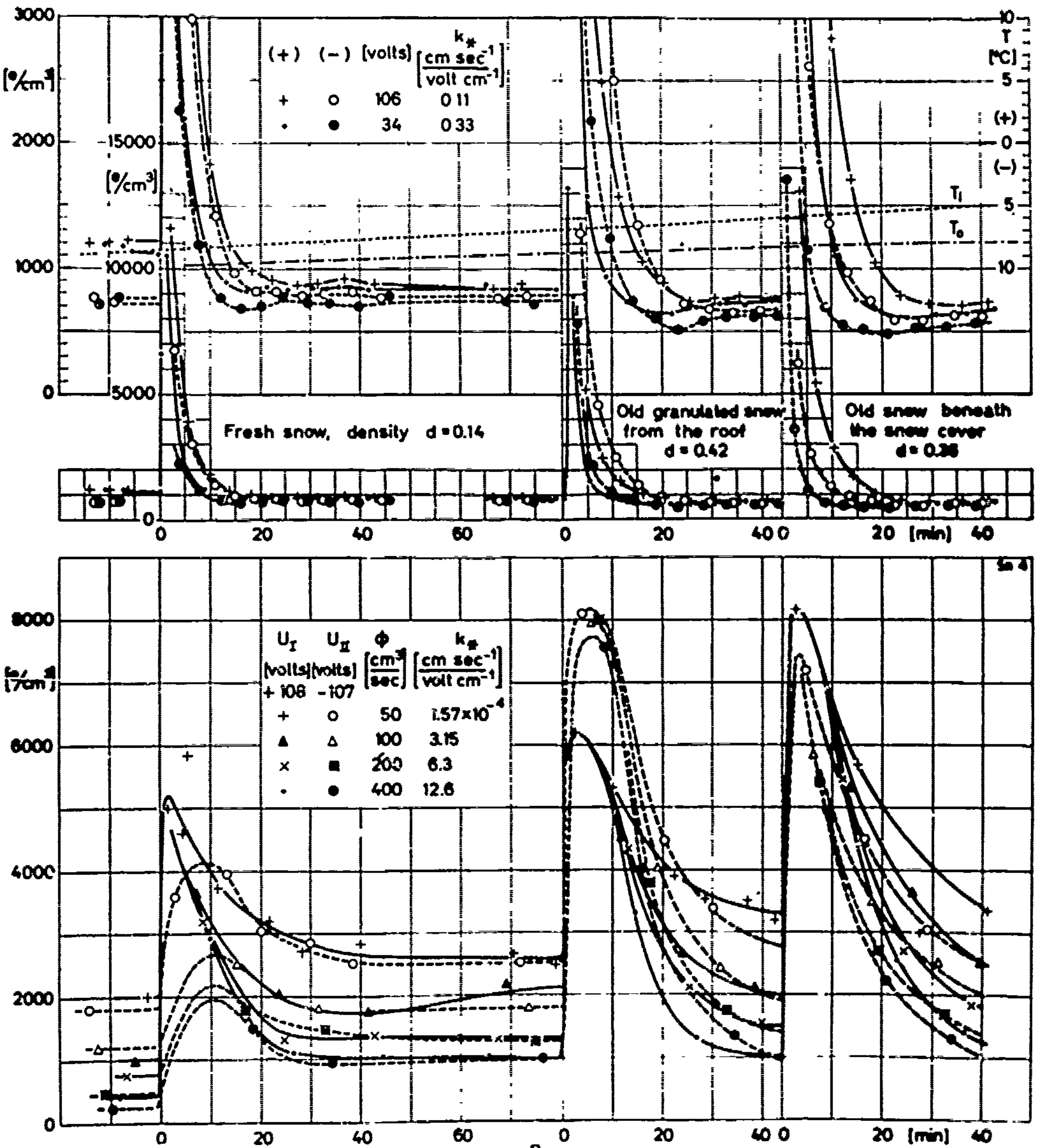


Fig. 5--Number of elementary charges e per cm^3 in the air when the effect of the blowing snow was measured with a Weger condenser (upper), and with an Israël large-ion counter (lower); T_i is the temperature in the test room; T_o, outdoor temperature

a value which is sufficient for creating corona discharge around the particle, and, as shown by investigations carried out at this Institute [NORINDER and SIKSNA, 1952 ab, 1953a; SIKSNA, 1952b, 1953], atmospheric ions are formed by the corona discharge. It is evident that the snow particle with the charge q = 700,000 e established by us when touching the collecting electrode had a diameter greater than $2\ r = 34\mu$, because corona was not expected from it, but particles with field on the surface of $E \geqq 30{,}000$ V/cm might be expected to be present in the air in greater amounts at the instant of separation of the electrified snow particles. Yet it is not easy to measure this higher initial charge of the electrified particles. Moreover, the particle mentioned need not necessarily have a diameter $2\ r = 34\mu$ for obtaining a field sufficient for corona. Some points on the surface of the snow particle may have smaller curvature and so a corona field may also be obtained on larger particles. References may be found in the literature [HENRY, 1953] to indicate that charge measured by static electrification of a body may be much less than that existing on the body during the

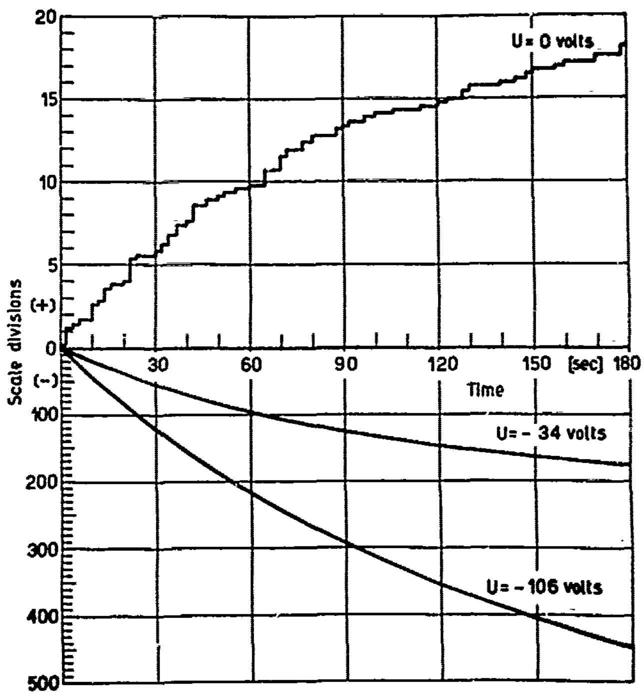


Fig. 6--Schematic reconstruction of the charging of collecting electrode in the Weger condenser when the controlling electrode was grounded (U = 0), and with potentials U = -34 and -106 volts

early stage of separation. The cause may possibly be found in dissipation of the charge by corona in the surrounding air, as indicated by MEDLEY [1950].

Thus, it is highly possible that a corona will be formed around a snow particle during the early stage of separation of a charged snow particle, and by the corona discharge, atmospheric small ions may be produced in the air. This process could be regarded as a possible source for production of atmospheric small ions in the air with blowing snow. Therefore, at least one part of the charges measured with the small-ion counter can be considered as small ions. Unfortunately, it was not possible to measure, with the arrangement used, the concentration of these ions sufficiently early after the inblast. It can be estimated to be of the order 10^3 - 10^5 cm^{-3} depending on the conditions for electrification.

In addition, it may be noted here that references may in fact be found in the literature on the dissipation of the initial charge by corona when electrifying a body by static electrification; but no indication is given, as far as we know, on the processes occurring in the air during the phenomenon. It would seem that this subject is worthy of investigation. An indication of the presence of charges in the air similar to those carried by small ions was also furnished by a phenomenon observed by us during our earlier experiments with snow [NORINDER and SIKSNA, 1953b, 1954]: the measured charge in the collector (when snow was poured through a funnel), and on the plate (when blowing snow), was larger when the collector or the plate had been discharged (collector or plate charged initially with a charge of a polarity opposite to the charge collected) than when the collector or the plate was charged, that is, when they had initially had a charge of the same polarity as that of the collected charge.

Interpretation of the measurements with the large-ion counter--Interpretation of the results of measurements with the large-ion counter is more difficult. When corona is formed around electrified

snow particles it might be expected that large ions could also be formed in the air in addition to small ions, as shown by our investigation of ions formed by corona [NORINDER and SIKSNA, 1952ab, 1953a; SIKSNA, 1952b, 1953]. However, the conditions may differ from those used by our corona investigation in case of electrified snow particles. Therefore, only part of the charges measured with the large-ion counter in air when blowing snow might be regarded as large ions with only one elementary charge. The predominant part of the charges measured must be attributed to particles

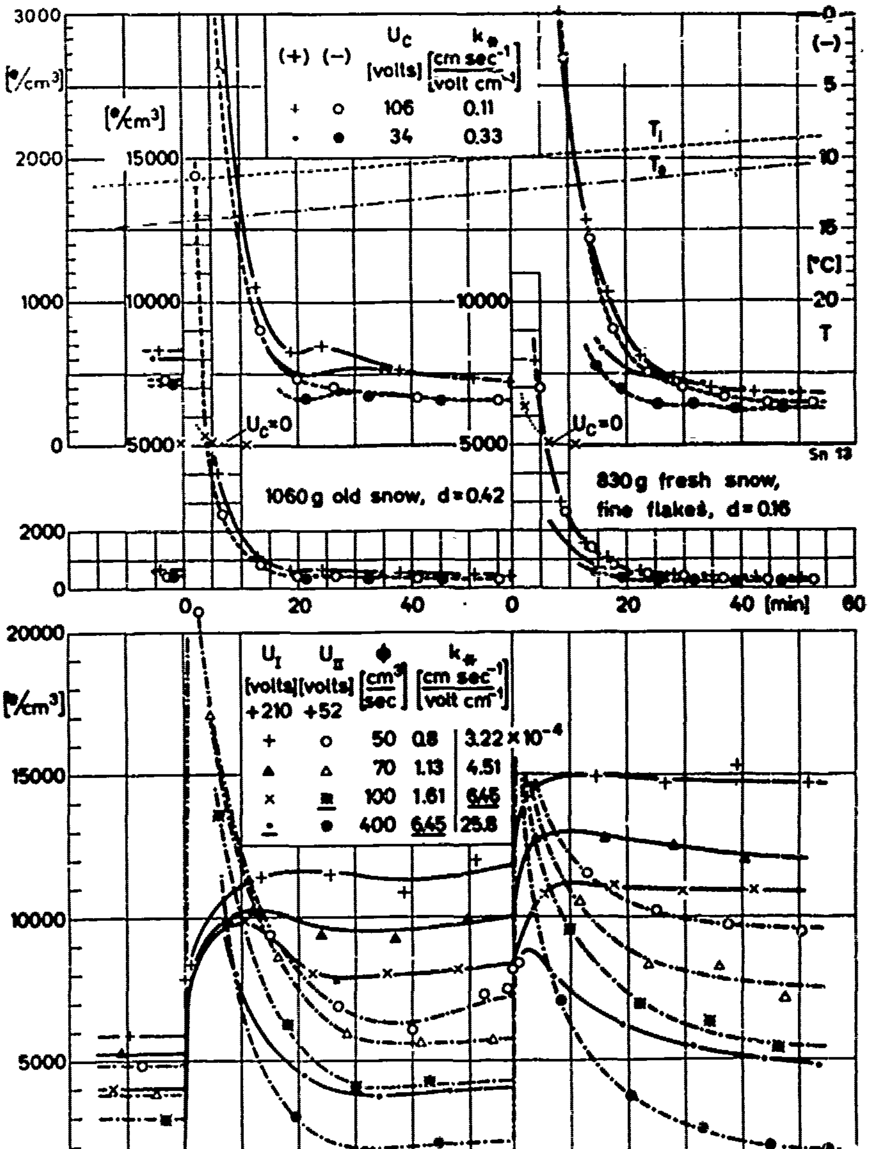


Fig. 7--Number of elementary charges e per cm^3 in the air when snow was being blown, measured with a Weger condenser (upper) and with an Israël large-ion counter (lower); T_1 (below zero) is the temperature in the test room; T_0, outdoor temperature

with greater than e charge. Indeed, these particles have a distribution greater than the mobility, as shown by the measurements when alternating the adjusted limiting mobility k_* of the large-ion counter (Fig. 5, 7, and 8). It must be pointed out here that under certain conditions immediately

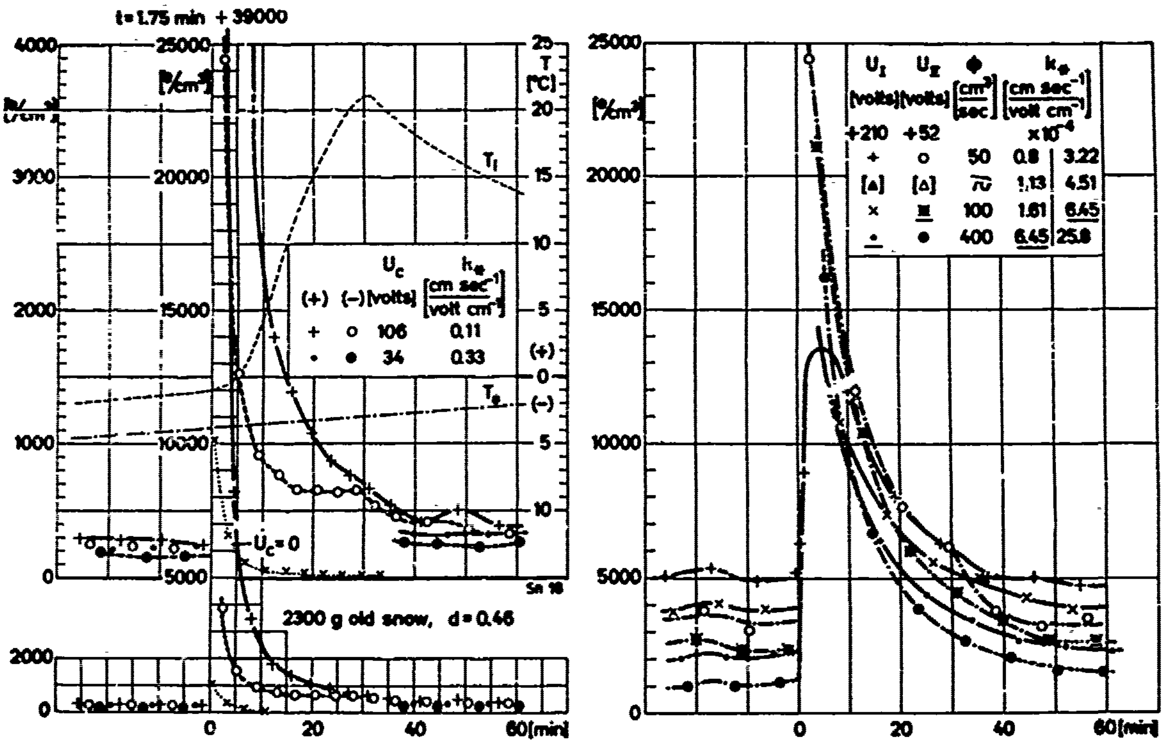


Fig. 8--Number of elementary charges e per cm^3 in the air when snow was being blown, measured with a Weger condenser (left), and with Israël large-ion counter (right); T_i (above zero) is the temperature in the test room; T_o, outdoor temperature

after inblast of the snow jet the number of charges measured with the large-ion counter adjusted at higher limiting mobilities k_*(with lower potential of the controlling electrode of the condenser) is greater than that at lower limiting mobilities (at higher potential of the controlling electrode) (Fig. 7). This fact indicates that the end effect of the condenser was acting during this stage of the measuring process [SIKSNA, 1952ab]. Also, from the time trend of the curves for the lower k = 0.8, 1.13, 1.61 × 10^{-4} cm sec^{-1}/volt cm^{-1} (Fig. 7) it may be seen that the predominant part of the charges measured must be attributed to particles with a charge greater than e. Throughout the period of measurement air was sucked from the test room at a speed of 200 ℓ/min mainly through the Ebert ion counter joined to the suction box for maintaining a sufficient replacement of the air in the suction box. The suspended charges must be removed from the test room with the air. In fact, the curves for the charges measured at the lower k_* did not decrease with time but remained on the high level for several hours, especially at a lower temperature in the test room. A kind of agglomeration of the charged particles may be the cause of this event. A more definite insight into this problem could be obtained by counting the particles by a method under preparation.

A general note must be added here. No difference of importance has been observed in the feature of the curves for positive and negative charges, nor was there any major difference whether the outlet tube of the snow jet was metallic or covered with ice.

Results of measurements at a higher temperature in the test room--A certain change of the shape of the measured charge-time curves was observed when the temperature was higher (above 0) in the test room. An example is shown in Figure 8. The first remarkable fact noted here was

that very large charges (up to 30-40 × 10^3 cm^{-3}) were measured with the small-ion counter at the beginning. Moreover, the charges measured at the grounded controlling electrode were also great. The curves obtained with the large-ion counter decreased more speedily wit. e. This last effect might be explained as follows: the small snow particles which may agglomerate nad ceased to exist at temperatures above zero. For the large charges measured with the small-ion counter the following consideration may be taken into account. The contact of the individual snow particles may be closer by friction and fragmentation at a temperature above zero, because it can be assumed that the particles are covered with a water layer on the surface. And according to the HELMHOLTZ [1879] classical theory of static electrification through friction, the main effect of rubbing two bodies is supposed to be to increase the area of the double layer on the surface of the bodies. If the charging particles were covered with a water layer the contact surfaces will be greater and thinner and the separated charges will also be greater. These greater charges of the snow particles are the source of a more intense corona discharge and the concentration of ions formed by corona must increase in this case.

It may seem that the Helmholtz theory of electrification by rubbing is somewhat outdated, but VICK [1953] has recently shown that this theory can be modernized and made a useful tool by incorporating into it ideas from the modern theories of solids.

Summary and outlook for extended research--(1) By the above measurements of the charges in the air when snow is blown it has been shown that with ion counters it is possible to separate the individual components of this complex event. Until now such separation has not been performed even for charges of different sign.

(2) It has been shown that with a small-ion counter two components were measured; small invisible snow particles, mostly with positive charge of several hundred thousands of elementary charges e, and possibly also atmospheric small ions which may be formed by corona discharge from the snow particles being highly charged during the early stage of their separation.

(3) An extended investigation of the small snow particles with high charge may be expected to yield additional results by using a more sensitive electrometric device suitable for rapid recording of charges.

(4) Investigation of the small ions formed by dissipation of the charge from the initially highly charged snow particles by corona discharge in the air may be of importance for a general study of the initial charge of bodies charged by static electrification.

(5) The fact that greater charge was measured with the small-ion counter when snow was being blown in the air at temperatures above zero might be explained by greater charge on the individual snow particles, and this greater charge on the individual snow particles may be explained by the closer contact existing between the particles during the impact because of a water layer on the surface of the snow particles. Intensified investigation of the small ions formed in such a way may be expected to yield more information on the contact electrification.

(6) Only part of the charges measured with the large-ion counter may be considered as atmospheric large ions. The predominant part must be attributed to particles with larger charges. A more definite insight into this problem could be obtained by counting the particles by a method under preparation.

(7) No attempt has been made so far to consider the experimental facts observed with a view to fitting them into an accepted theory, for it seemed to us that our knowledge of the experimental side of the subject must first be further extended.

References

CHALMERS, J. A., Electric charges from ice friction, J. Atmos. Terr. Phys., v. 2, pp. 337-339, 1953.

HELMHOLTZ, H., Studien über elektrische Grenzschichten, Ann. Phys. u. Chem., v. 7, pp. 337-382, 1879.

HENRY, P. S. H., Survey of generation and dissipation of static electricity, Brit. J. Appl. Phys., Sup. 2, pp. 6-11, 1953.

MASON, B. J., A critical examination of theories of charge generation in thunderstorms, Tellus, v. 5, pp. 446-460, 1953.

MEDLEY, J. A., Frictional electrification and gaseous discharge, Nature, v. 166, pp. 524-525, 1950.

NORINDER, H., On the measurement and nature of atmospherics produced by electric discharge in snow squalls and from other sources, Tellus, v. 1, no. 2, pp. 1-13, 1949.

NORINDER, H., and R. SIKSNA, Ions formed by corona discharge, IVA (Stockholm), v. 23, pp. 234-245, 1952a.

NORINDER, H., and R. SIKSNA, Ions formed in a room by negative wire corona, Ark. Fys., v. 6, no. 14, pp. 127-140, 1952b.

NORINDER, H., and R. SIKSNA, Ions formed in a room by positive wire corona, Ark. Fys., v. 6, no. 25, pp. 255-261, 1953a.

NORINDER, H., and R. SIKSNA, On the electrification of snow, Tellus, v. 5, no. 3, pp. 260-268, 1953b.

NORINDER, H., and R. SIKSNA, Experiments concerning electrification of snow, Ark. Geofys., v. 2, no. 3, pp. 59-89, 1954.

PEARCE, D. C., and B. W. CURRIE, Some qualitative results on the electrification of snow, Canad. J. Res., v. 27 (A), pp. 1-8, 1949.

SCHAEFER, V. J., Properties of particles of snow and the electrical effects they produce in storms, Trans. Amer. Geophys. Union, v. 28, pp. 587-614, 1948.

SIKSNA, R., Measurements of large ions in the atmospheric air at Uppsala, Ark. Geofys., v. 1, no. 18, pp. 483-518, 1952a.

SIKSNA, R., Mobility spectra of ions formed in a room by negative corona discharge, Ark. Fys., v. 5, no. 26, pp. 545-564, 1952b.

SIKSNA, R., Mobility spectra of ions formed by positive corona discharge, Ark. Fys., v. 6, no. 28, pp. 279-286, 1953.

SIKSNA, R., and A. METNIEKS, Aufladung eines isolierten Rohrs bei Durchströmen von ionisierter Luft und Absorption der Ionen, Zs. angew. Phys., v. 5, pp. 454-461, 1953.

SIMPSON, G., and F. J. SCRASE, Distribution of electricity in thunderclouds, Proc. R. Soc., London, A, v. 161, pp. 309-352, 1937.

STÄGER, A., Experimentaluntersuchungen über Kontaktelektrisierung von staub- und wolkenförmig zerteilten Körpern, speziell von Schnee als gewitterbildenden Faktor, Ann. Phys., Leipzig, v. 76, pp. 49-70, 1925a.

STÄGER, A., Weitere Untersuchungen über Kontaktelektrisierung bei fein zerteilten Körpern, Ann. Phys., Leipzig, v. 77, pp. 225-240, 1925b.

U. S. ARMY-NAVY PRECIPITATION-STATIC PROJECT, Proc. Inst. Radio Eng., v. 34, pp. 156-177, 234-254, 1946.

VICK, F. A., Theory of contact electrification, Brit. J. Appl. Phys., Sup. 2, pp. 1-5, 1953.

POINT DISCHARGE

J. Alan Chalmers

Senior Lecturer in Physics
Durham Colleges in the University of Durham
Durham, England

Abstract--The following matters are discussed: the part played by point discharge in the transfer of charge between cloud and Earth; the relation between point discharge and field strength; point discharge at natural and artificial points; space charge due to point discharge; effect of point discharge on rain.

Introduction--Point discharge, also called corona discharge and St. Elmo's fire, occurs whenever a point is at a difference of potential from its surroundings sufficient for there to be a volume of air in which the field is large enough for ionization by collision to occur. The actual value of the necessary potential difference depends mainly on the shape of the point. When point discharge is occurring, ions of both signs are produced, those of one sign traveling through the point, while those of the opposite sign move away from the point in the air, producing what is called the space charge.

In atmospheric electricity, point discharge can occur at natural points, for example, trees and mountain tops, and at artificial points on buildings, etc., but, in general it is not possible to make any direct measurement of the current through the points. However, if an insulated point is set up, the current through it to the Earth can be measured with a galvanometer, and is usually found to be of the order of microamperes. Whether there will be point discharge from a particular point at any given time depends mainly on (a) the electric field at the time, as measured over level ground, (b) the height of the point, and (c) the shape of the point. Other factors which enter are (d) the presence of natural space charge close to the ground, as this alters the potential difference between the point and its surroundings, (e) the pressure, and perhaps (f) the conductivity of the air and (g) the wind speed and direction.

Distinction between atmospheric and laboratory point discharge--Although many experiments on point discharge have been carried out under laboratory conditions, these can seldom be used in relation to atmospheric point discharge. The reason is the vast difference in scale, in particular in regard to the effect of the space-charge ions. In laboratory experiments the electrodes are so close together that the space-charge ions are only present for a small fraction of a second, while under atmospheric conditions they often take several minutes to move up to the cloud.

Because the same ions are present in both types of measurement, it is quite impossible to achieve any useful scale model, and results that are to be used for atmospheric point discharge must be obtained by observations in the atmosphere.

Point discharge as a factor in charge transfer between cloud and Earth--As was first pointed out by WORMELL [1927] point discharge is an important factor in the transfer of charge from clouds to Earth in disturbed weather. How important a factor clearly depends upon the number of discharging points and the current through each of them. Wormell attempted to estimate this by setting up an artificial point which he hoped would be about equivalent to a tree, and then counting the trees higher than his point in a given area. SCHONLAND [1928] attempted to get closer to a correct estimate by supporting a typical tree on insulators, but it would seem from his photograph that his tree was more isolated than in natural conditions and so not completely typical.

These results sufficed to show that point discharge probably brings more charge to the Earth during storms than either lightning or precipitation.

Effective separation of points--Measurements of the point discharge current through a single point can only provide the total point-discharge current over an area if one can assume an effective separation of discharging points equivalent to the measuring point. Since the natural points are at different heights and differ in shape, etc., and so in discharging efficiency, it is unlikely that there

will be one effective separation that is applicable for all conditions. When the field is small, there may be point discharge at high trees, etc., but none at the measuring point, so the effective separation is zero. As the field increases and discharge occurs at the measuring point, the effective separation increases; but, for very high fields, there will be a great number of points which are discharging, so that one might expect the effective separation to decrease again. Thus the effective separation can be expected to vary with the field and any estimate of an effective separation cannot be very exact. Early estimates of effective separation by WORMELL [1927], SCHONLAND [1928], and WHIPPLE and SCRASE [1936] were based on counting of trees in an area.

More recently, three indirect methods have been used. SIMPSON [1949] and CHALMERS [1951] have considered the relation between rain charge and point-discharge current and have obtained values for the density of the point discharge current; this will be discussed later (see Point discharge and rain currents). SMITH [1951] has used measurements of the recovery of the field after close lightning flashes, and, by considering this to be due to the space charge in the atmosphere traveling to the Earth as point discharge current, he has obtained the point discharge current density, which, with the actual current through a single point, gives the effective separation. And CHALMERS [1953] has assumed the distribution of field beneath a thunderstorm at Kew and has calculated the necessary spacing of points, similar to the one used by WHIPPLE and SCRASE [1936] at Kew, so that the total current beneath a thunderstorm shall equal that measured above a storm by GISH and WAIT [1950].

It turns out that the effective separation of points at Kew as found by these indirect methods is less, by a factor of about two, than the estimate of WHIPPLE and SCRASE [1936].

These methods of estimating the effective separations of discharging points are very indirect and clearly it would be most desirable to get more direct knowledge if possible. We are trying three methods of doing this at Durham, as will be discussed later (see Methods proposed).

Relation between point discharge and field--The point discharge current from a particular point depends on the field, and WHIPPLE and SCRASE [1936] found approximate agreement with $I = a(F^2 - M^2)$ where I is the current, F the field at the Earth nearby, and a and M are constants.

Others, for example CHIPLONKAR [1940] and HUTCHINSON [1951], have found general agreement with this formula, but Hutchinson found humps' in the curve, which he was able to explain as caused by discharges at points lower than the one used. LUTZ [1941] and HUTCHINSON [1951] also found that, when the field and point discharge current change sign, the field change precedes the point discharge change, this also being explained in terms of space charge from lower points.

Another important result is that of CHIPLONKAR [1940], who found that four points close together gave, under similar conditions, less total current than a single point.

It must be realized that the constant a in the Whipple-Scrase formula depends not only on the height and shape of the point but also on its relation to other points.

The alti-electrograph--The alti-electrograph of SIMPSON and SCRASE [1937] made use of point discharge to measure electric fields below and in thunder-clouds. Two sets of points attached to a balloon at different heights gave point discharge, which was recorded by pole-finding paper. Though originally intended merely to give the sign of the current, and hence of the field, the width of the trace was used to give the magnitude of the current; to obtain an estimate of the field, the Whipple-Scrase relation was assumed and the constant a determined by measurement of the field at the Earth at the commencement of the ascent. The conditions of point discharge are very different for the alti-electrograph and for the fixed point and it may well be incorrect to assume that the Whipple-Scrase formula holds or, if it does, that the constant a is independent of height.

The alti-electrograph results, interpreted as they have been, do not show an increase of field on rising from the Earth to the cloud. Yet, if point discharge is occurring, there must be space charge rising from the points, and there seems to be no mechanism to remove this; but if it rises,

there must be an increase of field below the cloud. It does not seem possible to think of wind removing the space charge; the same wind would carry the balloon with it! The only way out of the difficulty seems to be that the interpretation of the point discharge current in terms of field is false, and though the point discharge current through the alti-electrograph does not increase with height, the field does.

The reality of the space charge between cloud and Earth is not only shown by the fact that the space charge must go somewhere, but also by other phenomena. The changes of field at a lightning flash from a small value of one sign to a large value of opposite sign is explained very simply in terms of the 'unmasking' of the space charge, and, as will be discussed later (see Point discharge and rain currents), the relation between rain charge and point discharge current appears to require the space charge.

Measurements with balloon--Many of the problems of point discharge are difficult to solve if one has to wait for natural point discharge in disturbed weather, because the conditions then are very unsteady. However, it is possible to get point discharge to occur in fine weather if one raises a point to a sufficient height, and then there will be much steadier conditions. This cannot lead to a solution of all the problems that arise in point discharge, because the single high point is in conditions very different from those for one of a number of points more or less similarly situated.

We have carried out at Durham a series of observations using a captive balloon to support the point and have been able to obtain a relation between the current through the point on the one hand and the height, the field and the wind-speed on the other; the field is that measured sufficiently far to windward to eliminate any effect of the balloon or of the space charge liberated by it. (This, incidentally, was proved by the absence of any noticeable field change when a flying balloon burst.) The results show agreement with the formula, $I = K\,(Fh)^{1.75}\,W^{0.25}$, where I is the current, F the field, h the height, and W the wind speed. The method could not be used for wind speeds above 25 km/hr, nor could the balloon be flown at heights above 200 m, so that the formula is verified over only a limited range. Measurements were confined to fine-weather conditions.

Multiple points were investigated and it was found that, under similar conditions, a group of eight points gave together about half the current from a single point.

Theoretical results--Neglecting the pulsed nature of point discharge, and considering an average over a large number of pulses, we see that the field near the point and hence the point discharge current, will be affected by the space charge produced and, when conditions are steady, a condition is set up in which the point discharge space charge limits the field near the point to just the value required to maintain the current. An increase of point discharge current would give more space charge and so decreased the field near the point, thus reducing the point discharge current again.

Assuming the space charge to travel from the point within a 'space-charge volume,' it is possible to deduce relationships between point discharge current and field. Two cases have been worked out, one for a point which is one of a rectangular array of points, and the second for a single point which is the only one producing point discharge.

In the first case, it is assumed that wind has no effect, space charge from above one point being blown to above another. If it is then assumed that the space charge remains within the space charge volume up to a certain height and above this it is uniform, we can suppose this height to be such that the field and potential are the same within as outside the space charge volume at this height, and it is then possible to deduce the Whipple-Scrase formula $I = a(F^2 - M^2)$.

In the other case, it is assumed that the space charge ions remain within the space charge volume up to the height at which their velocity in the field is equal to the wind velocity and above this they are completely dispersed. On this assumption one obtains a relation $I = KF^{2-x}\,W^x$ where W is the wind velocity; the value of x depends on the shape of the space charge volume. The balloon results quoted above agree with this, giving x about 1/4.

Total point discharge current below a cloud--In discussing point discharge, the usual sequence of ideas has been to consider the cloud to set up a field at the Earth, and this field then produces point discharge, so that one expects more total point discharge current the more and the better exposed are the discharging points. This, however, is a wrong way of regarding the matter, since the more the point discharge, the more the space charge in the air and so the more the field is reduced by this space charge.

It is preferable to consider that the separation process within the cloud provides a certain current to be dissipated downwards and this is nearly the same whatever may be the surface conditions below; if there are few points, the field is high and each point gives a large current, but with more points, the field becomes less. This is dealt with in more detail by CHALMERS [1952].

Point discharge and rain currents--SIMPSON [1949] found a relation between rain current and point discharge current, and suggested that this could be accounted for if the falling rain drops capture the rising ions, as suggested by WILSON [1929]. However, Simpson found that the charges acquired by the raindrops would only fit with the theory if the charges were acquired in fields considerably higher than those near the Earth, fields such as would be expected from the effects of point discharge space charge but not found by the alti-electrograph. The same conclusions were reached from the observations on single drops of HUTCHINSON and CHALMERS [1951], with a detailed explanation in terms of the ion-capture process by CHALMERS [1951]. These results allowed of a determination of the effective separation of discharging points. The work has been carried further by SMITH [1951] who measured the charges on drops of different sizes falling at almost the same time, and accounted for the differences in charge by the same ion-capture process.

Methods proposed--In order to make further advances some ideas are being tried at present or will be shortly. To continue the balloon work, we are using a mast of sufficient height to give point discharge in fine weather and we hope to be able to extend the results obtained by the balloon; the disadvantage is, of course, that there is little variation of height possible, and the mast cannot easily be removed to test for its influence on the field.

In an attempt to measure the actual point-discharge current through a single tree, we have put sets of screws in a tree at two different heights, connecting each set together and joining the two sets through a galvanometer of low resistance; in this way we hope to be able to short-circuit part of the point-discharge current flowing down the tree and measure it. Results so far are hopeful but we cannot yet say more.

We are hoping to try the experiment of making a tree, or perhaps first our mast, the 'primary' of a 'transformer' of which the 'core' is to be a ring of magnetic material around the tree and 'secondary' is to be windings round this ring. In the secondary circuit we should get an output, to be amplified, which is the differential of the current in the tree; by graphical, or perhaps electronic, integration we get the actual current--we hope. Or it may be that we can detect and measure the individual current pulses in the point discharge current. This idea is as yet only in the stage of planning.

To leeward of a discharging point, there is a decrease of field, owing to the effect of the space charge. By using field measuring machines to windward and leeward of a discharging tree or group of trees, it may be possible to determine the current without touching the dischargers themselves. Clearly the effect on the field depends on the wind speed, but we hope that, by measurements with the mast, we can establish a relation which we can then apply to trees. This work is only in a preliminary stage but shows promise.

I come now to observations I hope someone will carry out, but which I am not in a position to do myself. If an instrumented aircraft could fly below a thundercloud, it would be possible to tell, once and for all, whether there is the increase of field predicted by the space-charge theory or not, or whether the field remains roughly constant as suggested by the alti-electrograph results. Alternatively, a field-measuring instrument, other than by point discharge, could be sent up in a balloon, perhaps with radio-sonde used for recording; if both a 'field mill' and point discharge could

record simultaneously, a great many questions could be answered. Perhaps an instrumented helicopter would be ideal for the purposes mentioned.

References

CHALMERS, J. A., The origin of the electric charge on rain, Q. J. R. Met. Soc., v. 77, pp. 249-259, 1951.

CHALMERS, J. A., Point discharge currents, J. Atmos. Terr. Phys., v. 2, pp. 301-305, 1952.

CHALMERS, J. A., The effective separation of discharging points, J. Atmos. Terr. Phys., v. 3, pp. 246-247, 1953.

CHIPLONKAR, M. W., Measurement of point discharge current during disturbed weather at Colaba, Proc. Indian Acad. Sci., A, v. 12, pp. 50-54, 1940.

GISH, O. H., and G. R. WAIT, Thunderstorms and the Earth's general electrification, J. Geophys. Res., v. 55, pp. 473-484, 1950.

HUTCHINSON, W. C. A., Point-discharge currents and the Earth's electric field, Q. J. R. Met. Soc., v. 77, pp. 627-632, 1951.

HUTCHINSON, W. C. A., and J. A. CHALMERS, The electric charges and masses of single raindrops, Q. J. R. Met. Soc., v. 77, pp. 85-95, 1951.

LUTZ, C. W., Uber die Spitzentladung bei Gewittern und Schauern, Beitr. Geophys., v. 57, pp. 317-333, 1941.

SCHONLAND, B. F. J., The interchange of electricity between thunderclouds and the Earth, Proc. R. Soc., A, v. 118, pp. 252-262, 1928.

SIMPSON, G. C., Atmospheric electricity during disturbed weather, Geophys. Mem. Lond., v. 84, pp. 1-51, 1949.

SMITH, L. G., Rain electricity, dissertation, Cambridge Univ., 1951.

WHIPPLE, F. J. W., and F. J. SCRASE, Point discharge in the electric field of the Earth, Geophys. Mem. Lond., v. 68, pp. 1-20, 1936.

WILSON, C. T. R., Some thundercloud problems, J. Franklin Inst., v. 208, pp. 1-12, 1929.

WORMELL, T. W., Currents carried by point discharge beneath thunderclouds and showers, Proc. R. Soc., A, v. 115, pp. 443-455, 1927.

THE ELECTRIC CHARGE OF RAINDROPS[a]

L. G. Smith

Geophysics Research Directorate
Air Force Cambridge Research Center
Cambridge, Massachusetts

Abstract--Rapid measurements of the electric charge and size of individual raindrops show that the large range of charge is not reduced by considering smaller time intervals. However, the average charge and the limits of the range of charge show definite relations to the size of drop. The relation for the average charge is similar to that obtained by considering the capture of ions (Wilson process) by drops falling in the region of the point discharge space charge below the cloud. A comparison with experiment indicates an increase of field strength with height. The large range of charge is attributed to the mixing, while falling, of drops leaving the cloud in regions of different current density.

The earlier investigations of the electric charge carried by individual raindrops have indicated that the relation connecting the charge and size of the drops is of a statistical nature. It was therefore felt that if any advance was to be achieved in a new investigation it would be necessary to sample the drops more rapidly than had been done previously.

The method of measuring the drops is shown schematically in Figure 1. The charge is measured by electrostatic induction on an open metal cylinder, ten cm in diameter, as the drop falls through; the mass of the smaller drops (0.2 to 2.5 mm diameter) being determined from the time

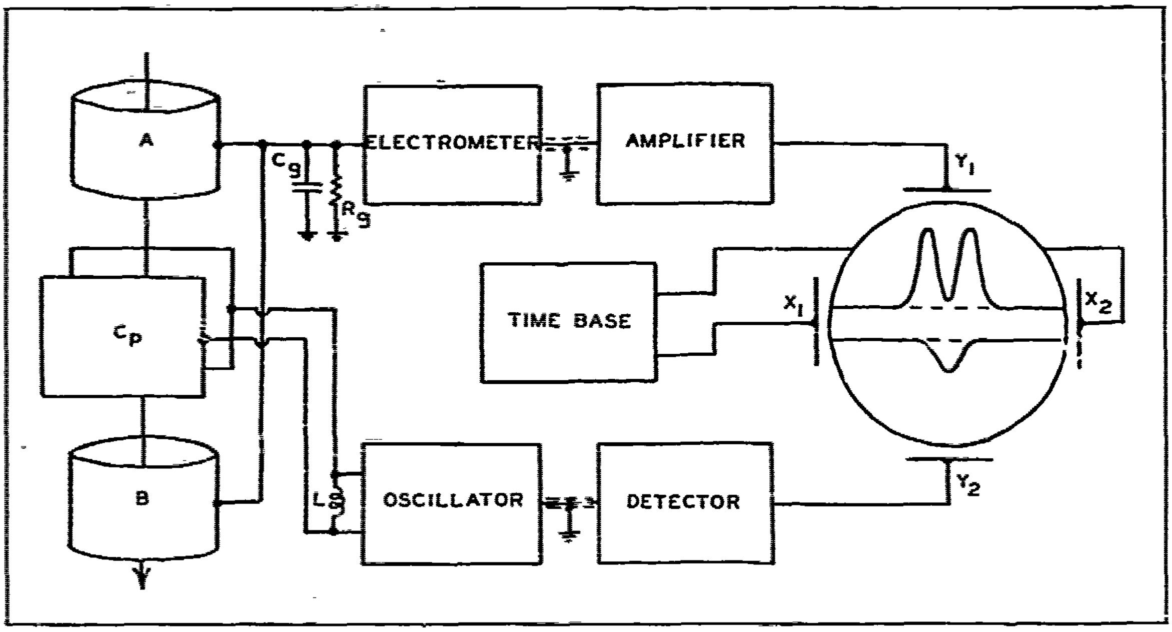


Fig. 1--Schematic diagram of apparatus measuring raindrops; upper trace on the double-beam oscilloscope records the electric charge and the lower trace the mass of the raindrops

[a]A detailed account of this investigation has been published in Q. J. Roy. Met. Soc., January, 1955.

of fall between two such cylinders. The mass of the larger drops (1.5 to 6.0 mm diameter) is measured by the change in capacity of a parallel plate condenser as the drop passes between the plates. This condenser is included in the tuned circuit of an oscillator and the momentary change in capacity produces a change in frequency which is then detected. The double pulse representing charge (upper trace) and the single pulse representing mass (lower trace) are displayed on a double beam oscillograph with a horizontal time base of three cps and photographed on film moving vertically at constant speed. This equipment has measured drops at rates up to 142 in one minute and 1200 in 16 1/2 minutes. Simultaneously point discharge current from an artifical point, field strength, rain current and rate of rainfall are also recorded.

Observations have been made during 42 periods when the rate of rainfall exceeded one mm per hour, totalling 9284 drops. At least 200 drops are required for an adequate statistical analysis of one of these periods. The general features of the observations are illustrated in Figure 2 which is one of the 15 periods in which more than 200 drops were measured. This period has been divided

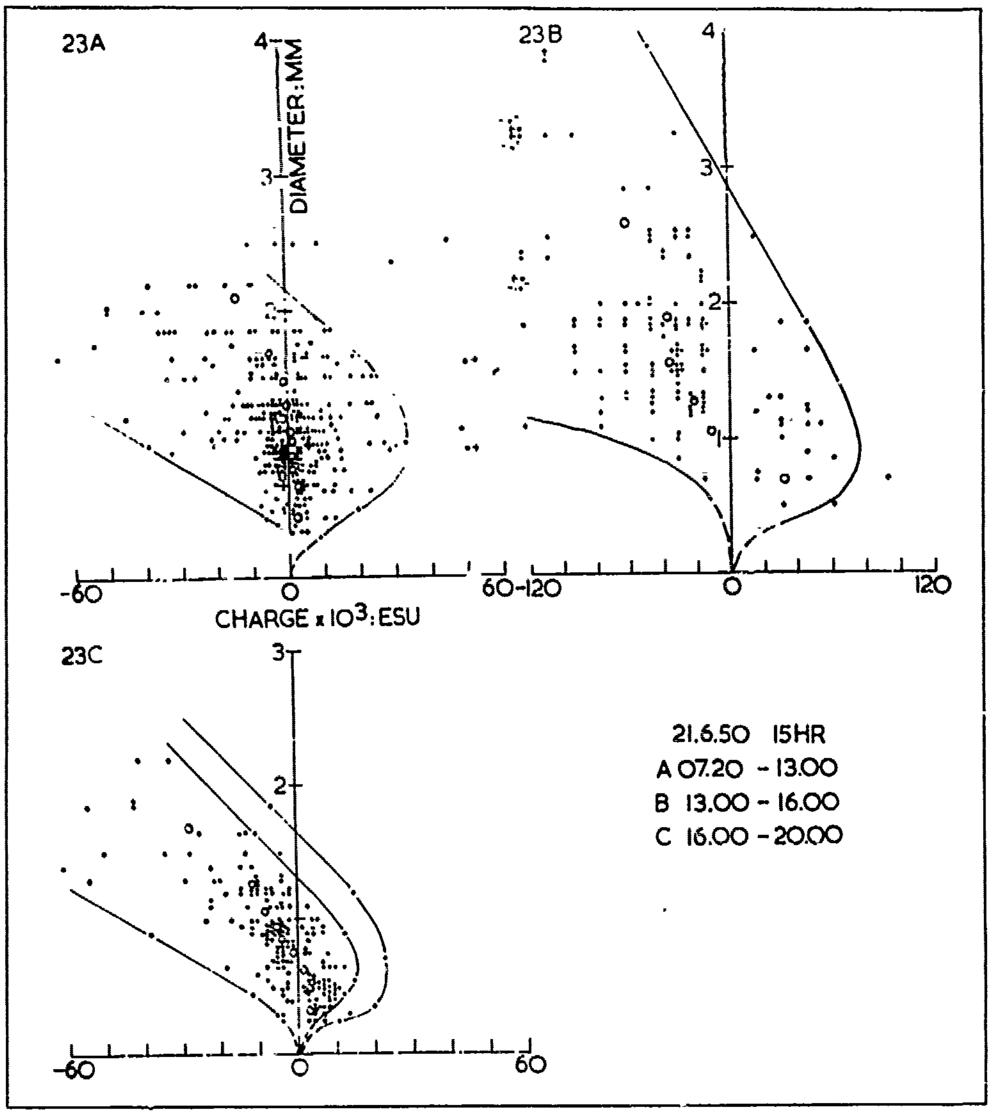


Fig. 2--Observation during period 23

into periods of 5 2/3, 3, and 4 minutes, each including about 200 drops. The rate of rainfall averaged 4, 25, and 5 mm per hour for the three periods of this thundershower. The individual drops are represented by points and the circles are the average charge for a small range in diameter.

The charge on each size of drop varies over a wide range, often including both signs. This is a characteristic of all the observations, including short periods when the field was steady. The average charge, however, shows a definite relation to the size; there is a certain size for which the average charge is zero, on smaller drops the average charge is one sign (positive in the case shown in Fig. 2) while the larger drops have average charges of the opposite sign. The limits of the range of charge also show some relation to size of drop. These relations are shown in Figure 3 for what is termed a positive distribution, the sign referring to the sign of the average charge on the smaller drops. Some observations are found to be negative distributions.

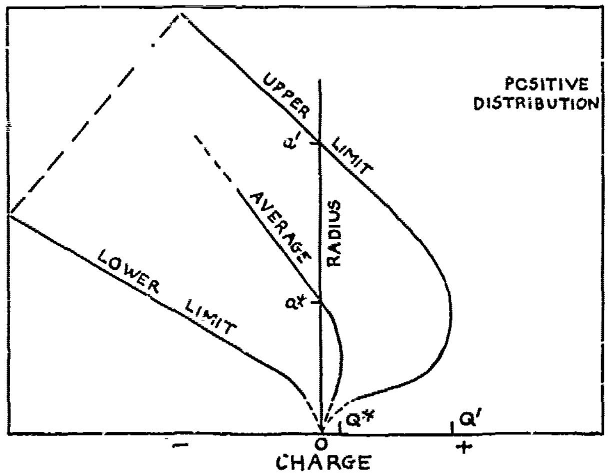


Fig. 3--The general form of the charge-size relation, positive distribution

The simultaneous observations of point discharge current and field strength show that the sign of the distribution, as defined above, and the sign of the field at the ground are opposite for 80 pct of the observing time. Thus, in general, the larger drops arrive at the ground with charges the same sign as the charge in the base of the cloud while the smaller drops have charges opposite to this. This indicates that the drops have modified their charges by capture of ions from the unipolar point discharge current below the cloud, only the smaller drops having sufficient time to reverse the sign of the charge. The equation of charging for this case of the Wilson process is

$$\frac{dQ}{dx} = \frac{\pi J(3Xa^2 + Q)^2}{3X^2a^2v_a} \quad \ldots\ldots (1)$$

where Q is the charge, a the radius and v_a the fall velocity of the drop; J is the current density of point discharge, X the electric field strength, and x the height above the ground. For the simplest case in which the field is assumed constant with height and the initial charge (at the height x_o) is given by $Q_o = 3nXa^2$, this equation may be integrated whence the charge on the drop arriving at the ground is given by

$$\frac{3Xa^2}{3Xa^2 + Q} = \frac{Jx_o}{Xv_a} + \frac{1}{1+n} \quad \ldots\ldots (2)$$

This expression is shown graphically in Figure 4 for n = 1 and for several values of the parameter $V = Jx_o/X$. The curves show the same general shape as the distribution shown in Figure 3.

The magnitude of a distribution may be characterized by the quantities Q and a as defined by Figure 3, the asterisk signifying the average charge and prime the upper limit of charge. It can be shown that these quantities are related to the product Jx_o by

$$Jx_o = -5.0 \times 10^3 Q^*/a^* \text{ esu} \quad \ldots\ldots (3)$$

which is independent of the value assigned to X and almost independent of n. The product Jx_o can be

determined from direct observations and compared with the value derived from the charge-size relation for the average charge of the drops. The pairs of values are within an order of magnitude for the ten periods for which data are available.

An estimate of the value of the field in the region of charging can be obtained from the relation

$$X = -4Q^*/a^{*2} \quad (4)$$

Comparison with values of the field measured at the ground show that the field in the charging region exceeds the field at the ground by a factor which averages 30. This increase is associated with the existence of the space charge of point discharge ions. The relation determining the value of the field at the cloud base is

$$X = (8\pi J x_0/k)^{1/2} \quad (5)$$

where k is the mobility of the ions. In Figure 5 a comparison is made between the values of the field in the region of charging obtained from the observations and the field at the cloud base obtained from the equation just given. There is good agreement supporting the interpretation given here.

The cause of the wide range of charge on the individual drops is indicated in Figure 5. It is attributed to the variation in field and current density at different points in the cloud base, the drops becoming mixed by lateral diffusion while falling. There is further evidence for this in the observations.

Thus a consistant picture can be built up to account for the main features of the observations of the electric charges of raindrops. The agreement between theory and experiment

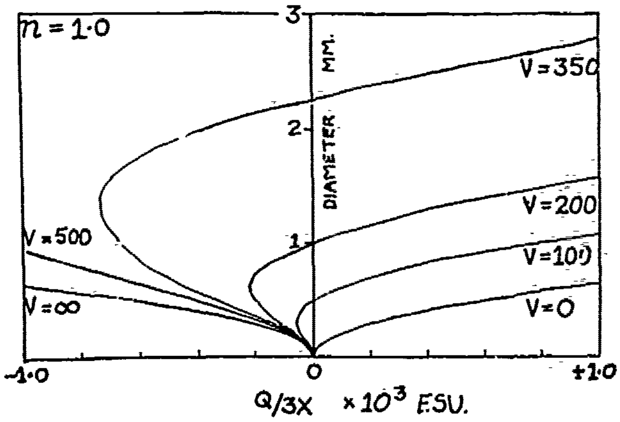


Fig. 4--The theoretical charge-size relation

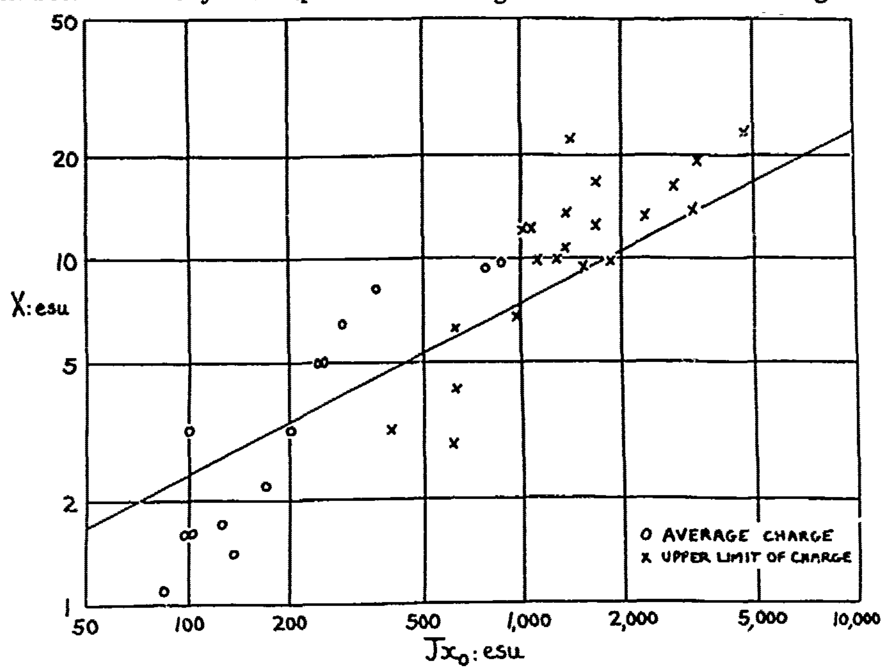


Fig. 5--The field in the charging region plotted against Jx_0

is not perfect but this can be ascribed to the use of a simple model to represent so complex a phenomenon as an electrified cloud and its environment.

I wish to acknowledge the advice and encouragement of T. W. Wormell of the Cavendish Laboratory, University of Cambridge, in this investigation.

THE SYSTEMATIC ELECTRIFICATION OF PRECIPITATION BY IONIC DIFFUSION

Ross Gunn

Physical Research Division, U. S. Weather Bureau
Washington 25, D. C.

Abstract--The author's recent investigations of droplet electrification by ionic diffusion are reviewed. Expressions are given for the enhancement of the equilibrium charge by the motion of the droplet relative to the environment. It is shown that simple ionic diffusion accounts for the free positive charge usually observed on mist and light rain.

An exact solution of the diffusion equations leads immediately to useful relations for the combination coefficients of ions and droplets. These agree well with observation.

Hyperelectrification of droplets by ionic diffusion in superposed electric fields is considered. Electric fields can profoundly modify the relative conductivities of the positive and negative ions near electrodes or cloud surfaces and, thus, greatly enhance the charges transferred to a droplet. Under disturbed weather conditions, the estimated charges are somewhat larger than those inferred from droplet measurements made on the ground under thunderstorms. The sign of the charge placed on droplets near the Earth's surface by hyperelectrification is opposite to that of the C. T. R. Wilson effect and, hence, tends to reduce the impressed electric field.

Introduction--The universal character of ionic diffusion has been noted by a number of investigators who have observed the transfer of free electrical charge to highly insulated conductors. For example, MILLIKAN [1911] noted in his pioneer determination of the size of the elementary charge, that although suspended oil drops carried a number of elementary charges, they were observed to acquire further charges of the same sign. Millikan correctly attributed this to the diffusion of the ions onto the drops and noted that their thermal motions provided the energy to overcome the normal repulsion between ions of the same kind. He also observed that the droplets picked up negative charges more easily than positive. ARNDT and KALLMANN [1925] worked out approximate expressions for the equilibrium charge acquired by insulated conducting spheres when ions of a single sign only were present and found that the equilibrium charges were very large. FRENKEL [1946] extended the calculation to the case when both ions were present but assumed that the ionic population just outside the droplet approached zero. Such an assumption is not justified. GUNN [1935] pointed out that the diffusion of ions and water vapor might selectively transfer electrical charge to atmospheric droplets and that this process approximated the behavior of concentration cells. On such an assumption, he worked out an association theory of thunderstorm droplet charging. The papers summarized here [GUNN, 1954, 1955, and PHILLIPS and GUNN, 1954] establish theoretical and experimental justification for this old hypothesis.

Equilibrium charge on a sphere at rest--The universal character of ionic diffusion and the frequent occurrence of conducting droplets falling freely in the atmosphere appeared to justify a careful investigation of droplet charging by ions. It has been assumed that ions obey the classical laws of diffusion and that any systematic motion imposed by free charges is proportional to the mobilities of the positive and negative ions, u_+ and u_-, and to the electric field. Moreover, arguments advanced by Debye and by Huckel have shown that the space charge outside any droplet in the atmosphere is widely dispersed and its influence on diffusion can be neglected. It is further assumed that waterdrops possess no intrinsic potentials at the water-air boundary so that selective adsorption of ions can be neglected. Subject to the above assumptions, an exact solution has been worked out for both the positive and negative currents to an isolated sphere immersed in the specified environment. When the positive and negative currents to the droplet are equal, the resulting steady state defines the equilibrium charge on the droplet. Exact expressions for the steady state are given in the basic paper [GUNN, 1954], but it is sufficient to note here that when the droplet radius is large compared to the mean free path and the diffusion is molecular, the equilibrium charge, Q_0, is determined by

$$\frac{N_+u_+}{N_-u_-} = \exp\left[\frac{e}{kT}\left(\frac{Q_0}{a} - \frac{Q_0}{R_0}\right)\right] = \frac{\lambda_+}{\lambda_-} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where e is the elementary charge, k is the Boltzmann constant, T is the absolute temperature, N_+ and N_- are the ionic densities of the positive and negative ions in the environment, u_+ and u_- are their mobilities, λ_+ and λ_- are the respective conductivities, a is the droplet radius and R_0 is the radius of the shell where the ionic equilibrium approaches that of the environment.

If the droplet is at rest with respect to its environment, this relation degenerates further into

$$Q_0 = a\left[\frac{kT}{e}\ln\frac{\lambda_+}{\lambda_-}\right] \qquad (2)$$

In this expression, the quantity of electricity is proportional to the radius of the droplet or its capacity and to a factor which measures the droplet's equivalent potential. This potential corresponds to the potential of a concentration cell closely approximating that assumed in an earlier publication [GUNN, 1935]. It is possible to work out the rate at which this equilibrium is established. We shall note here only that if the positive and negative ion densities are somewhat similar and approximate N, then the charge varies with the time, t, according to

$$Q = Q_0\left[1 - \exp(-4\pi eNut)\right] \qquad (3)$$

and the effective charging time, τ therefore approximates

$$\tau = 1/4\pi eNu_{\pm} \qquad (4)$$

Equilibrium charge on a sphere in motion with respect to an ionized environment--Evaporation experiments have shown that the relative motion between droplets and their environment profoundly modify the rate of diffusion. Accordingly, we have obtained a solution for the basic diffusion equations that permits a determination of the augmentation of free charge resulting from relative motion.

In considering the processes of charge transport of ionized air, it is convenient to think in terms of small packets of ionized air that move towards the droplet, make transient contact with it to exchange ions and are finally merged again with the environment [KINZER and GUNN, 1951]. When the droplet motion increases with respect to the ionized environment, the packets of ionization are swept closer and closer to the droplet. This increasing motion results in shrinking the ionized environment around the droplet and this systematically increases the diffusion gradients. From aerodynamic arguments, it has been found possible to determine the effective thickness of the shell separating the droplet from its environment in terms of the droplet size and its relative velocity [KINZER and GUNN, 1951].

The expression for the equilibrium charge given by (1) is in such a form that the thickness of the transition layer between the droplet and its environment can be incorporated directly into the expression by identifying it with $R_0 - a$. Making this substitution and employing the relation connecting the thickness of the transition layer with the relative velocities and other droplet parameters, it is found finally [GUNN, 1954] that the equilibrium charge for a falling droplet is

$$Q_0 = a\left(1 + F\sqrt{\frac{aV}{2\pi D}}\right)\left[\frac{kT}{e}\ln\frac{\lambda_+}{\lambda_-}\right] \qquad (5)$$

where F is a constant approximating unity, V is the relative velocity of droplet and environment, and D is the effective diffusion coefficient given by

$$D = \frac{N_+D_+ + N_-D_-}{N_+ + N_-} \qquad (6)$$

The reader may verify by substitution of appropriate quantities that the relative motion for a large raindrop may increase the rest charge by a factor of 30. This augmentation of charge is by no means negligible even for mist and light rain.

Experiment and theory--Although the derived relations were based on solid theoretical grounds, it seemed worthwhile to test their adequacy in the laboratory. In a paper by PHILLIPS and GUNN [1954], a detailed experimental exploration of the mechanisms has been carried out and experimental curves given for the equilibrium charge as a function of the various parameters. Interested readers should consult the original paper, but it may be stated that within the accuracy of measurement the experimental results are entirely consistent with the theoretical formulation of (5).

The combination coefficient of ions and droplets--The solution of the diffusion equations leads directly to values for the rate of transfer of positive and negative ions to the droplet. Therefore, if there are N_0 droplets per unit volume and the ionic density outside is known, one finds that the rate of disappearance of ions per unit volume is proportional to both these quantities. The proportionality factor is the so-called combination coefficient appearing explicitly in the exact solution. The reader is referred to the original paper [GUNN, 1954] for the derivation, but it may be noted here that the combination coefficients are given by

$$\eta_{+o} = \frac{4\pi kT u_+ a}{e[1 + (Qe/2akT) + \ldots]} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$\eta_{-o} = \frac{4\pi kT u_- a}{e[1 - (Qe/2akT) + \ldots]} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Attention is directed to the fact that the combination coefficient is finite even though the droplets carry no charge. But if the droplet is charged sufficiently to raise the potential energy of an ion at its surface to anything like the thermal kinetic energy of the ion, then according to (7) and (8), the droplet charge modifies the rate of combination. Obviously, if the droplet charge and ionic charge are of the same sign, the combination is decreased whereas if they are of opposite sign the probability of combination is increased. Since these combination coefficients are proportional to the radius of the droplet, it should be evident that measurements should exhibit considerable scatter, just as is actually observed.

Equilibrium charge carried by falling mist and light rain--Although there is wide disagreement as to the free charges brought down by heavy rain, almost all observers report that the charge brought down by mist and very light rain is positive. For example, SCRASE [1938] measured the charge brought down by rain for a period of two years and found that 93 per cent of such precipitation was positively charged and that the specific charge approximated 0.46 esu/gm. Other workers have similarly reported a positive excess for the smaller particles. Since mist and light rain are formed in the lower atmosphere where many experimental data provide reliable estimates for the relative conductivities for the positive and negative ions, it seemed of interest to estimate from (5) the charge on such precipitation. In Figure 1 is given a curve showing the values predicted by (5) for freely falling droplets of various radii with the environmental conductivity ratios specified on the curves.

It may be seen that mist and light rain of radii between 4 and 10×10^{-3} cm will carry a specific charge approximating 0.5 to 1.0 esu/gm. In estimating this charge, the measurements of the conductivity ratios near the surface of the Earth by SHERMAN [1937] have been adopted, namely, $\lambda_+/\lambda_- = 1.34$. There is evidence that the conductivity ratio for the positive and negative ions varies with altitude and with the occurrence of precipitation and, hence, variability in sign and magnitude of the charge may be anticipated. For comparison with the normal electrification to be expected in the lower atmosphere, Figure 1 also includes a curve for the case where $\lambda_+/\lambda_- = 10$.

Hyperelectrification of droplets--The above paragraphs summarize the general behavior of droplets subject to ordinary thermal diffusion. However, special circumstances frequently occur in the atmosphere that result in the transfer of extraordinarily large charges to falling droplets. It seems necessary to mention these conditions under a special heading.

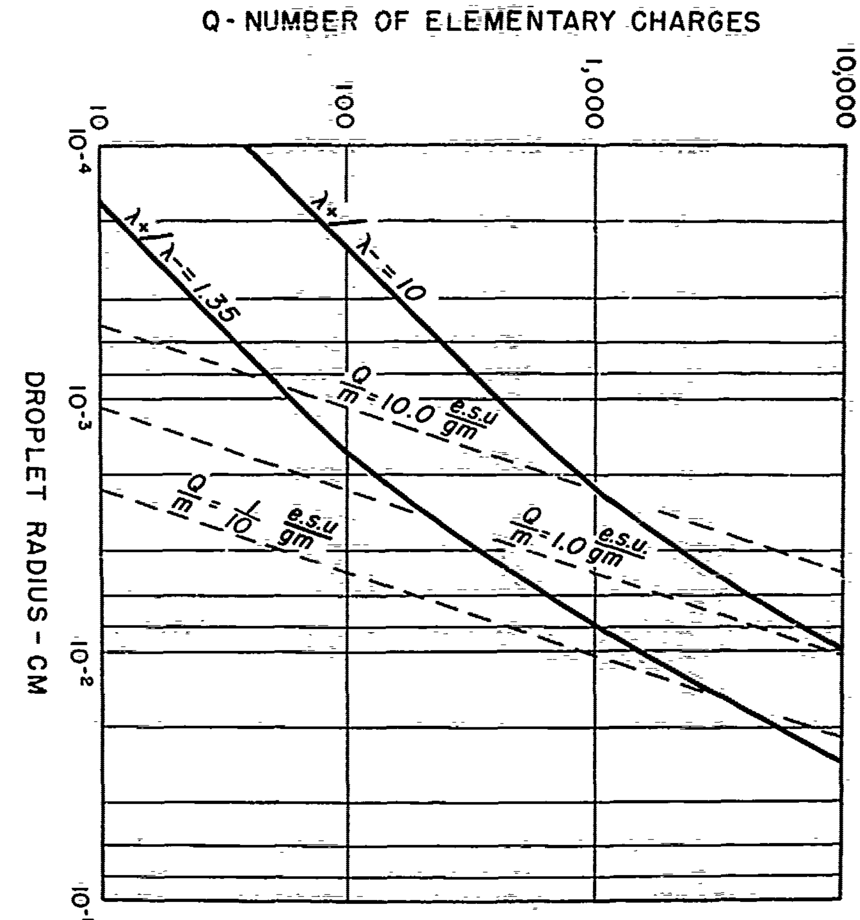


Fig. 1--Equilibrium charge on atmospheric droplets as a function of their radius; dashed lines define equal charges per unit mass of rain

The intensity of the cosmic rays and radioactivity determines the normal ion-pair production in the atmosphere. The average values of the electrical conductivity and the conductivity ratio for the positive and negative ions are accordingly determined by these ionizing mechanisms. But their actual magnitude at a particular point in the atmosphere is determined by the diffusion of the newly produced ions onto nuclei or droplets and by electric fields that may redistribute the ions in space. If the electrical conductivities for the positive and negative ions are equal, it is clear from (5) that diffusion would produce no important electrical effects.

The conductivities of the positive and negative ions are almost invariably different, and some droplet electrification both by diffusion and by electrical conduction is present. It is emphasized here that sometimes the conductivity due to one type of ion may be a hundred times that of the other, and under such circumstances, it is clear from (5) that hyperelectrification of droplets will occur. The accumulation of ions of a single sign near the Earth's surface is well known. For example, large surface electric fields usually sweep out almost all of the upward moving ions and λ_+/λ_- becomes large or small compared to unity, according as the surface charge is negative or positive. Similarly, GISH [1932] has noted in his discussion of electric conductivities that "when the electric intensity reaches about $\pm$ 300 volts or more per meter" and "of normal sign (inward), then the negative conductivity drops abruptly to approximately zero value whereas the positive conductivity remains quite unchanged." Droplets exposed to such an environment will clearly become highly charged. It is of interest to note that under these conditions the free charge transferred to droplets is opposite in sign to that of the C. T. R. Wilson effect. Space does not permit

us to consider in detail droplet charging of this character, but it should be pointed out that cloud boundaries exposed to electric fields will exhibit similar electrode effects. This is because the positive and negative conductivities within the cloud are now known to be at least an order of magnitude smaller than that observed outside. Experimental and theoretical studies of droplet charging by diffusion and by conduction under the conditions mentioned above are already well advanced and will be reported shortly.

Conclusion--The detailed investigation of the diffusion of ions onto droplets has shown that diffusion plays a very important role in determining the ionic equilibrium of the atmosphere and the charge carried to the ground by quietly falling mist and light rain. The specific charge transferred to small droplets normally approximates 1 esu/gm. Thermal diffusion acting on ions that have been systematically concentrated by electric fields results in a hyperelectrification of atmospheric droplets that promises to explain the extraordinarily large charges sometimes observed on thunderstorm rain.

References

ARNDT, P., and H. KALLMAN, Über den Mechanisms der Aufladung von Nebelteilchen, Zs. Physik, v. 35, pp. 421-441, 1925.

FRENKEL, J., Influence of waterdrops on the ionization and electrification of air, J. Physics, USSR, v. 10, pp. 151-158, 1946.

GISH, O. H., Observed air-earth current and maintenance of the Earth's charge, Terr. Mag. and Atm. Elec., v. 37, pp. 361-363, 1932.

GUNN, R., Electricity of rain and thunderstorms. Terr. Mag. and Atm. Elec., v. 40, pp. 79-106, 1935.

GUNN, R., Diffusion charging of atmospheric droplets by ions and the resulting combination of coefficients, J. Met., v. 11, pp. 339-347, 1954.

GUNN, R., The electrification of mist and light rain in the lower atmosphere, J. Geophys. Res., v. 60, pp. 23-27, 1955.

KINZER, G. D., and R. GUNN, The evaporation, temperature, and thermal relaxation time of freely falling waterdrops, J. Met., v. 8, pp. 71-83, 1951.

MILLIKAN, R. A., The isolation of an ion, a precision measurement of its charge and the correction of Stokes law, Phys. Rev., v. 32, pp. 349-397, 1911.

PHILLIPS, B. B., and R. GUNN, Measurements of the electrification of spheres by moving ionized air, J. Met., v. 11, pp. 348-351, 1954.

SCRASE, F. J., Electricity on rain, Geophys. Mem., v. 9, no. 75, 1938.

SHERMAN, K. L., Atmospheric electricity at the College-Fairbanks Polar Year Station, Terr. Mag. and Atm. Elec., v. 42, pp. 371-390, 1937.

DISCUSSION
CONCERNING THE PAPERS PRESENTED ON THE MORNING OF MAY 21, 1954 AND OTHER PROBLEMS OF THE THUNDERSTORM AND DISTURBED WEATHER

T. W. Wormell presiding

Dr. Wormell -The subjects to be discussed this afternoon seem to fall rather naturally into four groups. I do not propose, however, that this should be a rigid division.

The first group is the electrical structure and charge generation in clouds, especially thunderclouds; the second, the lightning discharge; the third, point and discharge current and its effect on the charging of raindrops; and the fourth, the charging of quiet continuous rain.

Dr. Kuettner--In Mason's estimate of the total thunderstorm charge cited by Wormell, the discharging of the particle by air conductivity is forgotten. This changes the estimate considerably.

Is there necessity to explain the Radar effect at the cloud base by a breakup of droplets in order to increase the droplet concentration? Is the increase of diameter not much more effective due to the sixth power?

Dr. Wormell--In both cases one needs updrafts for explanations of the observations.

Dr. Kuettner--If the external field is in your (Wormell's) opinion more effective than 'spontaneous' effects of the growth of precipitation particles then you should get all the electrical effects also in 'warm' showerclouds.

Dr. Wormell--It may well be that spontaneous effects start it, but it seems to me that when the field gets big enough, it is an induction buildup controlled by the field itself rather than the spontaneous charge. Does anyone else have any comments on Dr. Kuettner's remarks?

From the Floor: I wish you would define 'spontaneous effects.'

Dr. Wormell--I would call a 'spontaneous effect' charging in the absence of an external field.

Mr. Reynolds--It seems one of the mechanisms you proposed this morning for the development of lower positive charge-center depended on up-draft in this region. It seems to me there is a lot of evidence from Dr. Byers' work and a little from some of our work, that you simply cannot count on the up-draft in the region of heavy precipitation. There almost has to be a down-draft in the region of heavy precipitation.

Dr. Wormell- -Well, I agree that is the generally accepted view, what I was saying was that this type of radar observation has been consistently obtained under these circumstances in this particular part of the thundercloud, it seems to me it might be inexplicable by any other assumption than that there is an up-draft just at the front edge of the region of heavy precipitation.

Mr. Reynolds--It is a possibility at least.

Dr. Byers--To that point, I might say it was not clear from your radar pictures that this rain had been very intense for a very long period of time, so it is likely that the down-draft barely started, I do not know. That is why I asked the question this morning as to the time intervals between the two radar pictures. Even knowing that does not tell us very much because this eight millimeters per hour of precipitation might have been going on for some time, and then suddenly you got a burst of heavy rain which will be the thing to cause the down-draft.

Dr. Wormell--The typical result seemed to be that one got an echo for about the first two minutes.

Dr. Byers--Yes. Unless we have more information, I do not think we can draw much in the way of conclusions as to whether there was a down-draft or not.

Dr. Chalmers--The process that works for the main charge in the thundercloud does not operate in the continuous rain cloud. This gives a criterion for a thunderstorm theory.

The total point discharge current below a cloud depends very little upon the nature of the ground beneath. So point discharge ions are available in any case.

Mr. Reynolds--I have a diagram which I think relates to what Dr. Chalmers has just said. This shows the development of the electric field as associated with the occurence of the initial radar echo. We think that the precipitation particles are of the order of 200 microns radius at the time we first detected the three-centimeter radar echo.

One can see that the charges begin to separate at about two minutes after the particles have reached the size of 200 microns radius, at any rate that is the time the surface fields begin to increase. I think this illustrates the point that the charge separation process is tied very directly to the precipitation process.

Dr. Weickmann--Mason based his theory on the preliminary results obtained by Dr. aufm Kampe and myself during investigations of the charge generation connected with riming. We found that these measurements were in error due to the generation of spray electricity on the nozzle of the sprayer as well as on the rimer. Such effects had been investigated previously for instance by Chapman. This same applies for Meinhold's measurements in an aeroplane.

Dr. aufm Kampe--And for Lueder's measurements, but not in the case of Reynold's experiments whose rimer was a slowly rotating device.

Dr. Chapman--With reference to Mr. Reynolds' paper, were the temperatures in the coulds determined?

Mr. Reynolds--By triangulating to determine the height of the cloud base, using the wet adiabatic lapse rate inside the cloud, and using the Albuquerque radiosonde to determine the cloud base temperature.

Dr. Chapman--It seemed to me that the charge centers seem to be at higher altitudes and at colder temperatures than generally are reported.

Mr. Reynolds--I think not, since we found negative charge centers from 0 to -33° C. Recently Marshall at McGill University reported radar observations of charge centers at -40°. I think our cold limit is just a bit warmer than Malan and Schonland's, and a bit colder than Simpson's, Workman's, Holzer's, and several others.

Dr. Chapman--It appears to me that the lightning dipole discharge which you measured occupies a very small volume of the total cloud, and I infer from this that the quantity of discharge must be a small fraction of the total charge in the cloud.

Mr. Reynolds--I am not sure how small a fraction. Our average charge involved in a single cloud discharge was about 26 coulombs. I believe this dipole occupies a volume about two kilometers in vertical extent.

Dr. Byers--My question concerns the statement about the down-draft along the outer surface of the cumulus cloud. We have made a number of measurements, and I think a number of others have made measurements in the vicinity of cumulus clouds and have not found this.

I think that the motion pictures are likely to be a bit deceiving. I think if they are examined it will be found that there is no sinking along the outer surface of the cumulus cloud except in those cases where the whole system is either sinking or getting ready to sink.

If the cloud subsides, the outer part subsides first. If the cloud is really growing fast, or growing at any appreciable rate I am sure there would be no downward transport visible in the outer surface of the cloud.

Dr. Vonnegut--I believe that whether there are downdrafts on the surface of cumulus clouds is a question subject to debate. Further investigation of this point is needed.

Dr. Chapman--First, as I understand the theory, downward drafts around the outside of the cloud are an essential part of the mechanism. Second, I believe corona from the ground will generate the positive ion space charge, or at least most of it, after things get under way. The question is: What happens over the oceans where presumably there are no points sticking up? Third, am I correct in assuming that it would be quite important to ascertain the conductivity inside the clouds, so that one could determine whether the raindrops, the droplets, or the ions carry most of the electricity?

Dr. Vonnegut--With regard to the corona question, I think, as far as I have been able to find, there are no data concerning the behaviour of water surfaces of the ocean or the lakes under intense electric fields. Laboratory experiments show that with intense fields, it is possible to get a spray of electrified droplets from a water surface, and presumably it is possible to get corona. The mechanism must be quite different over a water surface, and one would expect that depending on the sort of wave systems you have there might be considerable variability. I think this is an exceedingly important thing to determine. As far as land surfaces are concerned, I think that possibly over deserts it may be difficult to get point discharges. I think that even there, there will usually be enough grasses and bushes to give corona.

Concerning the conductivity within a cloud, I think this is of considerable importance, and there are few data concerning conductivity within clouds. Dr. Gunn recently reported conductivity measurements in simulated clouds in the laboratory and reported values of one tenth to one third of the normal value of conductivity.

Dr. Pluvinage--I have made some conductivity measurements inside of clouds. I, too, have found values from one-tenth up to one-third of the normal conductivity.

Dr. Chalmers--I think there is one point I did not have time to mention this morning which is relevant to what Dr. Vonnegut said in connection with point discharge. The total point discharge current below a thunderstorm cloud is not very dependent on the nature of the surface beneath. One has a certain rate of generation of charge within the cloud. that the rate of dissipation of charge upwards and downwards will be determined by the generating process in the cloud. The number and size of discharge points will determine when the discharge begins but will have small influence on the total discharge current.

Dr. Wormell--In the limit of these circumstances, will not the field build up?

Dr. Chalmers--Either that, or one will get it dissipated by normal conduction current. The field will be so big that the conduction current would be large enough to do it. That will provide the positive ions going into the cloud just the same, if the rest of Dr. Vonnegut's theory is valid.

Dr. Kuettner--I might add that I think that in the individual cases in cumulus clouds, down drafts occur on the outside. For the thundercloud as a whole, I doubt that this is true. Now, you should expect with this mechanism that the negative charge accumulates on the base of the cloud, not at the minus ten degree level where it is generally found. Also, you would have to expect the same mechanism working on warm shower clouds in the tropics.

Dr. Vonnegut--Starting with the last question, relating to the tropical clouds according to this theory, there is a critical size for the cloud in order to produce electrification. As I recall this critical size is of the order of ten kilometers diameter. I believe your first question relating to the down-drafts on the surface of the cloud is debatable: in order to prove whether my theory has anything to it, I will have to make more accurate measurements.

Mr. Reynolds--I should like to comment on Dr. Vonnegut's statement concerning the minimum diameter of storms. Very often, the New Mexico clouds are much smaller and show active electrification.

Dr. Vonnegut--I appreciate that. Duststorms are a source of rather intense space charge which I think might reduce the critical size.

Dr. Weickmann--I have the feeling that under Dr. Vonnegut's theory the thunderstorm would act as a consumer of the electirc field and not as a generator. If this were true I believe the electric field of the Earth should be generated by something other than by thunderstorms.

Dr. Vonnegut--The current that my theory requires is essentially the current which has been observed. It is in the direction necessary to maintain the positive charge in the ionosphere.

Mr. Reynolds--As I understand the mechanism it appears to involve a boot-strap technique, it is the atmoppheric field which causes the thunderstorm, so we cannot have a thunderstorm producing the fair-weather atmospheric field.

Dr. Vonnegut--I prefer calling it not a boot-strap technique, but a closed cycle. The thunderstorm charges the ionosphere and leaves a legacy of space charge in the lower atmopshere for future thunderstorms. It is a cycle in which the thunderstorm needs the space charge and also produces it.

Dr. Kuettner--I think it is the same argument that was raised against Wilson's theory and against all theories that are based on the effect of the electric field.

Dr. Wormell--The argument could be raised against the Wimshurst machine.

Are there any other further comments? If not, we will pass on to the general subject, lightning, on which there were three papers by Prof. Bricard, Prof. Tamura, and Dr. Norinder. Dr. Kuettner has a comment on Prof. Tamura's paper.

Dr. Kuettner--This paper seems to explain one basic difficulty of the thunderstorm. The problem, namely, is the short time factor of the recovery curve. It shows that this can be the effect of a superposition of two curves which give the illusion of an exponential curve with small time factor.

Mr. Reynolds--We have observed some recovery curves which are nearly linear with time. The recovery times are fairly long.

Dr. Wormell--These are at what distances?

Mr. Reynolds--They are between two and four miles. I do not know exactly.

Dr. Wormell--I will agree that at moderate distance one may get linear recoveries and all sorts of complications.

Are there any other remarks about the recovery curves or the lightning discharge in general? If not, I must pass on to the papers on point discharge and the charge on raindrops. Dr. Chapman, I think, had some question on Dr. Chalmer's paper.

Dr. Chapman--Dr. Chalmers and I used different space-charge distributions beyond a corona point for he was interested in the case where the wind and field were at right angles, and I was interested in the case behind an airplane where the field and wind, in this case much larger, were parallel.

I am prepared to believe that in many cases several points will give more current than a single point (for we have such measurements). On the other hand it is not inconceivable to me that with very closely spaced points there will be less current than from an isolated point because of shielding and space charge effects.

Dr. Chalmers--I showed no significant difference due to wind.

Dr. Chapman--This result seems correct for the case of many points when the wind and field are at right angles, but when I spoke of wind I had in mind wind or flow of air past an airplane.

Dr. Norinder--I should like to ask if some calibrations have been carried out with a corona point method when the point was located in an atmosphere filled up with small droplets or ice crystals. I suppose that such water particles can influence the results. There is an evident discrepancy between field measurements of Simpson and Scrase of 10,000 volts/m in clouds and the field necessary to initiate a lightning discharge.

Dr. Chalmers--I think that in a good many cases, the balloons of Simpson got into the active part of the thundercloud and were destroyed. The point was very recently made that the maximum values they got were the maximum that they could measure. When they got sparking inside the apparatus, they could no longer measure the magnitude of the current at all. What I was talking about was that they did not find an increase of field below the cloud, not whether they found big fields inside the cloud.

Dr. Norinder--Point-discharge methods were used by others in Florida and at Argentine Peak near Denver where fields having values of 40,000 and 150,000 volts/m, respectively were measured. There is a significant discrepancy between these values. It may be, for instances, that we have to reckon with different types of thunderstorms, the tropical type in Florida and frontal storms in higher latitudes.

Dr. Gunn--The electric fields inferred from the measurements of Simpson and Robinson in thunderstorms, namely, about 100 volts/cm is too low by about a factor of 10. Precipitation Static Project measurements showed that fields of 1000 to 2000 volts/cm inside an active thunderstorm occur rather frequently. Just prior to a lightning stroke at 13,000 ft the electric field measured on the belly of the airplane was 3400 volts/cm. Discussions with Dr. Robinson reveal that he and Dr. Simpson now agree that their earlier measurements are of doubtful accuracy.

Dr. Wormell--Those are inside the clouds. Has anyone measured field underneath the clouds?

Dr. Gunn--This was inside, Simpson and Robinson gave us to understand.

Dr. Norinder--When one is talking about conditions inside clouds based on field measurements outside, if there are showers to the ground we have to consider the decrease in field. We cannot neglect the cylinder of a precipitation.

Dr. Gunn--I would like to make one comment on this. We flew a good many of these thunder storms, and there is one characteristic which I always thought was tremendously important, and which I reported in the literature. Just before our aircraft enters the cloud, the electric field would typically read about 200 volts/cm maximum. As soon as one dodges inside the cloud, the field would jump by a factor of two to four. So I think the observation shows very clearly that there are surface distributions of charge on the cloud and that the common assumption that the distribution is a dipole is a rather poor fiction.

I repeat, these measurements mean that there are large surface distributions of free charge near the cloud boundary; and therefore, one must be careful how he interprets the electric field data.

Mr. Reynolds--I have a comment on Dr. Chalmers' paper. If I understood correctly, he referred to the lower positive charge in the base of the cloud. It's location seems to me very important. Simpson's colleagues usually found the charge near the zero degree isothermal surface, occasionally, at warmer temperatures.

Dr. Chapman--Simpson gave various average values for the temperature of the so-called Q charge from +2°C to +5°C.

Mr. Reynolds--I have forgotten the average value. At any rate, Dr. Kuettner also found the charge near zero degrees, and this is where we find it. In our case this is not far from the base of the cloud, but it is important to know whether it is at the base or well into the cloud when one considers the point discharge mechanism as its cause. Even eight degrees centigrade is well up in the clouds in Simpson's study, is it not?

Dr. Chalmers--Yes.

Dr. Chapman--Dr. Gunn's field measurement in an aircraft of 3400 volts/cm prior to a lightning strike was converted by Gunn to 1600 volts/cm vertical component of the free field by the form factor due to the shape of the fuselage. Several people have reported 600-800 volts/cm as common within clouds. I do not think the balloon measurements are essentially in conflict. Simpson and Scrase got 100 volts/cm; I found 200 volts/cm. It may be that the calibrations are in error since in calibrating close to the ground (Simpson) or in the laboratory (Chapman) there are electrodes near by. Now in any space charge situation in the absence of wind, if the far electrode is at a great (or infinite) distance, as is the case for a balloon in the air, a great (or infinite) voltage is required for a finite current. The speed of a balloon is small and it has but little wind past its corona points. Therefore in the free atmosphere, extrapolations based on measurements near electrodes may not be valid, and a greater field may be required for a given corona current than was assumed. In the corona current expression

$$i = \epsilon_o (FkV^2/\ell + GvV + H\ell v^2/k)$$

for the balloon situation the first term may be smaller tha thought because of large distances, and the second term may yield large values of potential V because of the small wind speed v. A measured current could imply a much greater field than had been supposed.

Dr. Chalmers--Simpson and Scrase actually did not calibrate their balloon in the laboratory. They measured the current through the balloon soon after it left the ground and measured the surface field simultaneously with a radioactive collector with a fixed point, so they did not have to extrapolate from laboratory measurements.

The problem I was up against this morning was whether the wire technique measures the field accurately. It ought to give relative values of the field, which should increase as the balloon goes up. They do not. Now, the possibility has occurred to me that the distortions of the field changes with

the height of the balloon above ground. If it does, one might explain no increase of current with height.

Dr. Chalmers--Smith's results show an apparent discrepancy with those of Hutchinson and Cl. s. This is because the drops measured by Hutchinson and Chalmers all fall in the lowest port. of Smith's curve.

Smith's results also serve to explain why nobody between Elster and Geitel and Simpson found the inverse relation between rain charge and field. The shielding used by many observers prevents the smallest drops from reaching the receiver and it is these which contribute most to the inverse relation.

Mr. Reynolds--I should like to make a comment which tends to confirm Dr. Smith's interpretation of the inverse relationship of the sign of precipitation charges to the sign of the field.

Dr. Kuettner found at his mountain observatory that the precipitation charge was almost always opposite to the sign of the field. We have found the same thing. Now, in thunderstorms over mountains, the field is large and therefore, the effect is enhanced to almost a one to one relationship.

Dr. Chalmers--I think the mirror image effect is not exactly what you mean. Simpson found two things. He found the inverse relation between charge and field, which I think is best described as inverse relation. He also found the mirror-image effect when the field and charge were changing sign. He found the field changing and the change in charge was almost a mirror image of the field.

Dr. Reynolds--This is quite what I mean. Following a discharge which causes a change in the sign of the field, the precipitation charge, within a half minute or a minute, changes sign. There is a bit of a lag, but it is almost a mirror image.

Dr. Chalmers--We have sometimes found when measuring field and charge that we get a 'W' pattern of field and then the rain charge follows the mirror image except in the center part of the pattern. It looks as if the center part of the 'W' pattern is connected with the charge of the rain, this being sufficiently strong to affect the field at the Earth's surface. It is surprising how much the charge in the column of rain can affect the field at the Earth's surface.

Dr. Smith--I agree with Dr. Chalmers' explanation.

Dr. Wormell--Finally there is the paper of Dr. Ross Gunn. Dr. Kuettner has a question about this paper.

Dr. Kuettner--Gunn's effect would be quite important in view of the great extension of the precipitating fronts over the globe. Can the experts present here give their opinion as to whether or not the mean positive conductivity is actually greater than the mean negative conductivity?

Mr. Faucher--I would like to point out to Dr. Gunn and Dr. Kuettner that in all our measurements, at least from 500 to 35,000 ft that the ratio of conductivity was 1 ± 0.1.

Dr. Parkinson--If I remember, the principal results from Watheroo, the ratio of lambda plus to lambda minus was something like 1.2. This was, of course, at low altitude, 800 ft above sea level, and at Huancayo, negative conductivity is somewhat higher than the positive but the positive small ion density is greater than the negative. There is a considerable difference between the positive and negative small ions at Huancayo.

Dr. Schilling--We find near the surface during undisturbed conditions a preponderance of positive conductivity over negative conductivity of about 15 to 20 pct. Of course, we have observed ratios as high as 1.5 on mountain tops, which may be due to the electrode effect caused by the geometry of the mountain. We also noticed that changes in the ratio of the conductivities were not

always clearly connected with field changes during disturbed weather apparently not being due to an electrode effect alone. It seems to me that Mrs. Sagalyn's results refer to undisturbed conditions during certain lows of the day at appreciable heights above ground. For this and other reasons, we cannot compare her results with our results in this respect.

Dr. Gunn--The work of Sherman in Alaska, for a period of 11 months showed that the ratio of the positive conductivity to the negative conductivity was 1.35 if my memory is right. The measurements in Tucson, summarized by Wait yields a value of this ratio of 1.2 or 1.3.

Gish and Wait published some data on conductivity as a function of altitude. From their data is it possible to compute the ratio of positive to negative conductivity? It is greater than unity near the surface and less than unity at 25,000 ft.

Gish's and Sherman's measurements in the Explorer II suggest a ratio greater than one and at moderate heights decidedly less than one at high levels. Since that matter has been raised there was a paper published by Sagalyn, Coroniti, and others in the Journal of Geophysical Research. They say one thing in the text and the curves give something different.

We need more data. At the surface and near the surface the data are overwhelming that ratio is greater than unity.

Dr. Gish--I agree I cannot see from the evidence that has been accumulated over the years any grounds for assuming that the positive conductivity at the surface is not more than the negative. The average ratio is about 1.2. It seems to me that one of the important problems we ought to tackle is direct measurement of mobility.

Mr. Coroniti--Dr. Gunn questions the soundness of our measurements. He stated that we should have measured simultaneoulsy positive and negative conductivity. Dr. Gunn and I have discussed, before this conference, the interpretation of our data; and hence, I see no reason to air that problem at this time. With respect to the simultaneous measurements of positive and negative conductivities, we essentially did measure both. The procedure was as follows: A flight path of 30 minutes duration was chosen. The measurements were made at a constant altitude, beginning at an altitude of 5000 ft, and repeated at 10,000, 15,000, 20,000, and 35,000 ft. For a 15 minute period the positive conductivity was measured and for the remaining 15 minutes negative conductivity. These were repeated many times. Considering the short interval of 30 minutes, I am certain that the measured values of conductivities would not have differed from the simultaneously measured values.

Dr. Gunn--All I said was we need more experimental data and should make them carefully. How about the electrical field on these airplanes. Some of the measurements show there was a good deal of scatter.

Mr. Coroniti--You probably know the B-17 used. It is the same aircraft which you used in your precipitation static experiments. To study the effect of surface charge of the plane on the measured conductivities we experimentally measured the variation of fair weather positive and negative conductivities with positive and negative electric fields due to surface charge on the aircraft. We found that the field had to attain a value greater than ten volts/cm before the values of conductivities are affected. For instance, a value greater than +10 volts/cm affects the values of positive and not negative conductivity and vice versa.

Our measurements were made in fair weather. In fair weather, the electric field due to surface charge on the B-17 never reached this value according to your published reports.

I agree with Dr. Gish. We should have measured the mobility at various altitudes. It is not an easy task. One of the parameters that gave us plenty of trouble was the accurate measurement of air flow.

APPENDIX 1

LIST OF PARTICIPANTS

Dr. M. J. aufm Kampe
Signal Corps Engineering Laboratory
Belmar, New Jersey

Dr. R. H. D. Barklie
Emscott
Burney Road
West Humble
Dorking, Surrey, England

Mr. Arthur E. Bent
Mt. Washington Observatory
Ripley Lane
Weston, Massachusetts

Prof. J. Bricard
Institut de Physique du Globe
Universite de Paris
191 Rue Saint-Jacques
Paris V^{e}, France

Mr. R. T. Burnight
Naval Research Laboratory
Washington 25, D. C.

Dr. H. R. Byers
Department of Meteorology
University of Chicago
Chicago 37, Illinois

Dr. J. Alan Chalmers
Department of Physics
University of Durham
Durham, England

Dr. Seville Chapman
Cornell Aeronautical Laboratory
4455 Genessee Street
Buffalo 21, New York

Mr. John F. Clark
Naval Research Laboratory
Washington 25, D. C.

Mr. S. C. Coroniti
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Mr. E. S. Cotton
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Capt. Paul M. Crumley
Air Force Cambridge Research Center
230 Albany Street
Cambridge 39, Massachusetts

Mr. Robert M. Cunningham
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Dr. Harold Curtis
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Dr. Jacob Dinger
Naval Research Laboratory
Washington 25, D. C.

Mr. G. Faucher
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Prof. J. Fuchs
Ramperstorffergasse 2
Vienna 55, Austria

Dr. O. H. Gish
2626 Sewell Street
Lincoln 2, Nebraska

Mr. Paul Goldberg
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Dr. Ross Gunn
U. S. Weather Bureau
Washington 25, D. C.

Mr. D. Lee Harris
U. S. Weather Bureau
Washington 25, D. C.

Maj. Clyde V. Hendricks
Air Research and Development Command
Baltimore 3, Maryland

Dr. A. R. Hogg
Commonwealth Observatory
Mount Stromlo
Canberra, Australia

Dr. Robert E. Holzer
Institute of Geophysics
University of California
Los Angeles 24, California

Mr. J. H. Hughes
Office of Naval Research
Washington 25, D. C.

Miss Margery C. Hyland
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Dr. H. Israël
Deutscher Wetterdienst
Meteorologisches Observatorium
Aachen, Germany

Dr. Heinz W. Kasemir
Deutscher Wetterdienst
Meteorologisches Observatorium
Aachen, Germany

Prof. L. Koenigsfeld
Institutet Royal Meteorologique
3 Avenue Circulaire
Uccle, Belgium

Mr. James H. Kraakevik
Naval Research Laboratory
Washington 25, D. C.

Dr. Joachim P. Kuettner
Air Force Cambridge Research Center
230 Albany Street
Cambridge 39, Massachusetts

Dr. H. E. Landsberg
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Dr. H. H. Lettau
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Miss Maria M. Mahoney
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Mr. Elwood Maple
Naval Ordnance Laboratory
Silver Spring, Maryland

Mr. Henry A. Miranda, Jr.
Physics Department
Fordham University
Bronx 58, New York

Lt. John W. Nelson
Bureau of Aeronautics
Department of the Navy
Washington, D. C.

Dr. Patrick J. Nolan
Physics Department
University College
Dublin, Ireland

Dr. Harald Norinder
Institutet for Hogspanningsforskning
Uppsala, Sweden

Dr. W. D. Parkinson
Physics Department
Fordham University
New York 58, New York

Dr. P. Pluvinage
Faculte Des Sciences
Institut de Physique
Universite de Strasbourg
Strasbourg, France

Mr. S. E. Reynolds
New Mexico Institute of Mining
and Technology
Socorro, New Mexico

Mr. Stanley Ruttenberg
Institute of Geophysics
University of California
Los Angeles 24, California

Mrs. Rita C. Sagalyn
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Dr. Vincent J. Schaefer
Munitalp Foundation
Schermerhorn Road
Schenectady, New York

Dr. G. F. Schilling
Institute of Geophysics
University of California
Los Angeles 24, California

Mr. C. Russell Smallman
Arthur D. Little, Inc.
Boston, Massachusetts

Dr. L. G. Smith
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Mr. Waldo E. Smith
American Geophysical Union
1530 P Street, N. W.
Washington 5, D. C.

Dr. C. G. Stergis
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

Dr. W. F. G. Swann
Bartol Research Foundation
Swarthmore, Pennsylvania

Prof. Yuichi Tamura
Geophysical Institute
Kyoto University
Kyoto, Japan

Dr. Florence van Straten
Office of the Chief of Naval Operations
Washington 25, D. C.

Dr. Bernard Vonnegut
Arthur D. Little, Inc.
Boston, Massachusetts

Dr. Helmut Weickmann
Signal Corps Engineering Laboratory
Belmar, New Jersey

Dr. T. W. Wormell
Cavendish Laboratory
University of Cambridge
Cambridge, England

Dr. P. H. Wyckoff
Geophysics Research Directorate
Air Force Cambridge Research Center
415 Summer Street
Boston, Massachusetts

GEOPHYSICAL RESEARCH PAPERS

No. 1. Isotropic and Non-Isotropic Turbulence in the Atmospheric Surface Layer, Heinz Lettau, Geophysics Research Directorate, December 1949.

No. 2. Effective Radiation Temperatures of the Ozonosphere over New Mexico, Adel, Geophysics R-D, December 1949.

No. 3. Diffraction Effects in the Propagation of Compressional Waves in the Atmosphere, Norman A. Haskell, Geophysics Research Directorate, March 1950.

No. 4. Evaluation of Results of Joint Air Force-Weather Bureau Cloud Seeding Trials Conducted During Winter and Spring 1949, Charles E. Anderson, Geophysics Research Directorate, May 1950.

No. 5. Investigation of Stratosphere Winds and Temperatures From Acoustical Propagation Studies, Albert P. Crary, Geophysics Research Directorate, June 1950.

No. 6. Air-Coupled Flexural Waves in Floating Ice, F. Press, M. Ewing, A. P. Crary, S. Katz, and J. Oliver, Geophysics Research Directorate, November 1950.

No. 7. Proceedings of the Conference on Ionospheric Research (June 1949), edited by Bradford B. Underhill and Ralph J. Donaldson, Jr., Geophysics Research Directorate, December 1950.

No. 8. Proceedings of the Colloquium on Mesospheric Physics, edited by N. C. Gerson, Geophysics Research Directorate, July 1951.

No. 9. The Dispersion of Surface Waves on Multi-Layered Media, Norman A. Haskell, Geophysics Research Directorate, August 1951.

No. 10. The Measurement of Stratospheric Density Distribution with the Searchlight Technique, L. Elterman, Geophysics Research Directorate, December 1951.

No. 11. Proceedings of the Conference on Ionospheric Physics (July 1950) Part A, edited by N. C. Gerson and Ralph J. Donaldson, Jr., Geophysics Research Directorate, April 1952.

No. 12. Proceedings of the Conference on Ionospheric Physics (July 1950) Part B, edited by Ludwig Katz and N. C. Gerson, Geophysics Research Directorate, April 1952.

No. 13. Proceedings of the Colloquium on Microwave Meteorology, Aerosols and Cloud Physics, edited by Ralph J. Donaldson, Jr., Geophysics Research Directorate, May 1952.

No. 14. Atmospheric Flow Patterns and Their Representation by Spherical-Surface Harmonics, B. Haurwitz and Richard A. Craig, Geophysics Research Directorate, July 1952.

No. 15. Back-Scattering of Electromagnetic Waves From Spheres and Spherical Shells, A. L. Aden, Geophysics Research Directorate, July 1952.

No. 16. Notes on the Theory of Large-Scale Disturbances in Atmospheric Flow With Applications to Numerical Weather Prediction, Philip Duncan Thompson, Major, U. S. Air Force, Geophysics Research Directorate, July 1952.

No. 17. The Observed Mean Field of Motion of the Atmosphere, Yale Mintz and Gordon Dean, Geophysics Research Directorate, August 1952.

No. 18. The Distribution of Radiational Temperature Change in the Northern Hemisphere During March, Julius London, Geophysics Research Directorate, December 1952.

No. 19. International Symposium on Atmospheric Turbulence in the Boundary Layer, Massachusetts Institute of Technology, 4-8 June 1951, edited by E. W. Hewson, Geophysics Research Directorate, December 1952.

No. 20. On the Phenomenon of the Colored Sun, Especially the "Blue" Sun of September 1950, Rudolf Penndorf, Geophysics Research Directorate, April 1953.

No. 21. Absorption Coefficients of Several Atmospheric Gases, K. Watanabe, Murray Zelikoff and Edward C. Y. Inn, Geophysics Research Directorate, June 1953.

No. 22. Asymptotic Approximation for the Elastic Normal Modes in a Stratified Solid Medium, Norman A. Haskell, Geophysics Research Directorate, August 1953.

No. 23. Forecasting Relationships Between Upper Level Flow and Surface Meteorological Processes, J. J. George, R. O. Roche, H. B. Visscher, R. J. Shafer, P. W. Funke, W. R. Biggers and R. M. Whiting, Geophysics Research Directorate, August 1953.

No. 24. Contributions to the Study of Planetary Atmospheric Circulations, edited by Robert M. White, Geophysics Research Directorate, November 1953.

No. 25. The Vertical Distribution of Mie Particles in the Troposphere, R. Penndorf, Geophysics Research Directorate, March 1954.

No. 26. Study of Atmospheric Ions in a Nonequilibrium System, C. G. Stergis, Geophysics Research Directorate, April 1954.

No. 27. Investigation of Microbarometric Oscillations in Eastern Massachusetts, E. A. Flauraud, A. H. Mears, F. A. Crowley, Jr., and A. P. Crary, Geophysics Research Directorate, May 1954.

No. 28. The Rotation-Vibration Spectra of Ammonia in the 6- and 10-Micron Regions, R. G. Breene, Jr., Capt., USAF, Geophysics Research Directorate, June 1954.

No. 29. Seasonal Trends of Temperature, Density, and Pressure in the Stratosphere Obtained With the Searchlight Probing Technique, ' uis Elterman, July 1954.

No. 30. Proceedings of the Conference on Auroral Physics, edited by N. C. Gerson, Geophysics Research Directorate, July 1954.

No. 31. Fog Modification by Cold-Water Seeding, Vernon G. Plank, Geophysics Research Directorate, August 1954.

No. 32. Adsorption Studies of Heterogeneous Phase Transitions, S. J. Birstein, Geophysics Research Directorate, December 1954.

No. 33. The Latitudinal and Seasonal Variations of the Absorption of Solar Radiation by Ozone, J. Pressman, Geophysics Research Directorate, December 1954.

No. 34. Synoptic Analysis of Convection in a Rotating Cylinder, D. Fultz and J. Corn, Geophysics Research Directorate, January 1955.

No. 35. Balance Requirements of the General Circulation, V. P. Starr and R. M. White, Geophysics Research Directorate, December 1954.

No. 36. The Mean Molecular Weight of the Upper Atmosphere, Warren E. Thompson, Geophysics Research Directorate, May 1955.

No. 37. Proceedings on the Conference on Interfacial Phenomena and Nucleation.
I. Conference on Nucleation.
II. Conference on Nucleation and Surface Tension.
III. Conference on Adsorption.
Edited by H. Reiss, Geophysics Research Directorate, July 1955.

No. 38. The Stability of a Simple Baroclinic Flow With Horizontal Shear, Leon S. Pocinki, Geophysics Research Directorate, July 1955.

No. 39. The Chemistry and Vertical Distribution of the Oxides of Nitrogen in the Atmosphere, L. Miller, Geophysics Research Directorate, April 1955.

No. 40. Near Infrared Transmission Through Synthetic Atmospheres, J. N. Howard, Geophysics Research Directorate, November 1955.

No. 41. The Shift and Shape of Spectral Lines, R. G. Breene, Geophysics Research Directorate, October 1955.